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# LIMITED EVALUATION OF SENSOR REQUIREMENTS FOR AUTONOMOUS AIR REFUELING RENDEZVOUS

(PROJECT MEDIUM RARE)


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DECEMBER 2003

FINAL TECHNICAL INFORMATION MEMORANDUM





AIR FORCE FLIGHT TEST CENTER
EDWARDS AIR FORCE BASE, CALIFORNIA
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

Technical Information Memorandum (AFFTC-TIM-03-06) Limited Evaluation of Sensor Requirements for Autonomous Air Refueling Rendezvous (JON) M03C1500 by the Commandant, US Air Force Test Pilot School (USAFTPS), Edwards Air Force Base, CA 93524-6485.

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# REPORT DOCUMENTATION PAGE

*Form Approved OMB No. 0704-0188*



| 1. REPORT DATE *(DD-MM-YYYY)* | 2. REPORT TYPE | 3. DATES COVERED *(From - To)* |
|---|---|---|
| 12-13-2003 | Final Technical Information Memorandum | 7 Oct to 28 Oct 2003 |

**4. TITLE AND SUBTITLE**
Limited Evaluation of Sensor Requirements for Autonomous Air Refueling Rendezvous
(Project Medium Rare)

**5a. CONTRACT NUMBER**

**5b. GRANT NUMBER**

**5c. PROGRAM ELEMENT NUMBER**

**6. AUTHOR(S)**

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**5d. PROJECT NUMBER**

**5e. TASK NUMBER**

**5f. WORK UNIT NUMBER**

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AND ADDRESS(ES)**
Air Force Flight Test Center
412th Test Wing
USAF Test Pilot School
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**8. PERFORMING ORGANIZATION REPORT NUMBER**
AFFTC-TIM-03-06

**9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
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**10. SPONSOR/MONITOR'S ACRONYM(S)**

**11. SPONSOR/MONITOR'S REPORT NUMBER(S)**

**12. DISTRIBUTION / AVAILABILITY STATEMENT**
Approved for public release; distribution unlimited.

**13. SUPPLEMENTARY NOTES**
CA: Air Force Flight Test Center Edwards AFB CA CC: 012100

**14. ABSTRACT**
This report presents the results of Project MEDIUM RARE, a limited evaluation of sensor requirements for UAV autonomous air refueling rendezvous. The overall test objective was to determine sensor field-of-regard and detection range requirements for an array of tanker aspect angles that would allow successful autonomous, UAV rendezvous. The Air Force Research Laboratory requested this testing. The USAF Test Pilot School, Class 03A, conducted 8 flight test sorties totaling 12.5 hours at Edwards AFB, California, from 7 Oct to 28 Oct 03. All test objectives were met.

**15. SUBJECT TERMS**
aspect angle detection range flight testing refueling in flight rendezvous sensors tanker aircraft AAR(air to air refueling) air refueling AAR(autonomous air refueling) refueling rendezvous field-of-regard UAV(unmanned air vehicle)

| 16. SECURITY CLASSIFICATION OF: Unclassified | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT | b. ABSTRACT | c. THIS PAGE | SAME AS REPORT | 92 | Jacob Hinchman |
| UNCLASSIFIED | UNCLASSIFIED | UNCLASSIFIED | | | 19b. TELEPHONE NUMBER *(include area code)* (937) 255 - 8427 |

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

20040722 037

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# EXECUTIVE SUMMARY

This report presents the test results for the Rendezvous for Air Refueling Experiment flight test program (MEDIUM RARE). The purpose of this test was to determine sensor field-of-regard and detection range requirements for unmanned air vehicle (UAV) autonomous air refueling operations. Primary emphasis was placed on collecting data to allow AFRL to perform a trade study on potential sensor configurations. Test conditions examined the impacts of rejoin geometry and UAV sensor capabilities on rendezvous success.

The overall objective of this test was to determine sensor field-of-regard and detection range requirements for a UAV to accomplish an autonomous air refueling rendezvous utilizing procedures similar to those in a fighter turn-on. There were two specific test objectives: to determine minimum sensor range for successful UAV-tanker rendezvous; and to evaluate the operational utility of the UAV turn-on procedures. All test objectives were met.

Testing consisted of simulating rendezvous procedures, collecting flight test data on the same procedures, and comparing the two sources of data to increase confidence in the simulation predictions. Simulation was performed using a custom created MATLAB® algorithm, and then compared to an Air Force Research Laboratory (AFRL) provided D-6 computer simulation. Flight testing was performed using two F-16B aircraft, with one aircraft assuming the role of the UAV and the other acting as the tanker. Aircrew maneuvered within prescribed limits to simulate UAV and tanker flight performance. Testing was accomplished at the AFRL specified tanker rendezvous altitude and speed of 28,000 ft and 417 KTAS (275 KCAS) and a UAV altitude and speed of 27,000 ft and 445 KTAS (300 KCAS). Flight testing emphasized high-aspect angle rendezvous conditions, as those conditions were the most stressing scenarios.

Flight test and D-6 flight simulation data were collected for a subset of the total number of rendezvous cases and verified the predicted minimum detection range. In general, when a rendezvous was unsuccessful, it was either due to the UAV-to-tanker line-of-sight exceeding the sensor's field-of-regard or UAV incursions of the tanker safety zone. The correlation of simulation and flight test results provided a high level of confidence in the predicted minimum sensor detection ranges for autonomous air refueling rendezvous.

Operational utility assessment focused on the impact of autonomous rendezvous on air refueling missions and general autonomous rendezvous design considerations. The rendezvous procedure was representative of current fighter turn-on procedures, and should not be objectionable to tanker pilots.

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# INTRODUCTION

This report presents the test results for the Rendezvous for Air Refueling Experiment flight test program (MEDIUM RARE) sponsored by the Air Force Research Laboratory Air Vehicles Directorate (AFRL/VACC). The purpose of this test was to determine sensor field-of-regard and detection range requirements for unmanned air vehicle (UAV) autonomous air refueling operations. Specifically, this program examined the impact of geometry, UAV sensor capabilities, and tanker maneuvering on rendezvous success. Testing consisted of simulating rendezvous procedures, collecting flight test data on the same procedures, and comparing those two sources of data to increase confidence in the simulation predictions. Simulation was performed using a custom created MATLAB® algorithm, and then verified using a D-6 flight simulation that AFRL provided. Flight testing was performed using two F-16B aircraft with one assuming the role of the UAV and the other acting as the tanker. Aircrew flew and maneuvered within prescribed limits to simulate UAV and tanker flight performance.

Flight test maneuvers were accomplished at the AFRL specified tanker altitude and speed of 28,000 ft and 417 KTAS (275 KCAS) and UAV altitude and speed of 27,000 ft and 445 KTAS (300 KCAS). Due to F-16B performance limitations at high gross weights, some test points were performed at 21,000 ft, 417 KTAS and 20,000 ft, 445 KTAS for the tanker and UAV, respectively. Primary emphasis was placed on collecting data to allow AFRL/VACC to perform a trade study on potential sensor configurations for future UAVs. The flight testing emphasized high-aspect angle rendezvous conditions, as those conditions were the most stressing rejoin scenarios.

AFRL/VACC, Wright Patterson AFB, Ohio requested this test. The responsible test organization was the 412$^{th}$ Test Wing (412 TW), Air Force Flight Test Center (AFFTC), Edwards AFB, CA. Five members of the USAF Test Pilot School (TPS) Class 03A functioned as the MEDIUM RARE test team and executed the test (reference 8). All simulation work was performed at TPS. AFRL supported simulation work by supplying a D-6 flight simulation with autopilot capability (reference 5). Flight testing was performed in October 2003 totaling eight F-16B sorties and 12.5 flight hours.

## BACKGROUND

AFRL/VACC teamed with the Defense Advanced Research Projects Agency in a joint program called Autonomous Air Refueling to investigate concepts for UAV in-flight refueling capability. AFRL has completed limited wind tunnel testing of a potential UAV design and has incorporated these results into a high-fidelity, D-6 simulation. In working with USAF Air Mobility Command and Air Combat Command, AFRL has also identified concerns for implementing a UAV air refueling architecture. Specifically, Air Mobility Command and Air Combat Command expressed great interest in minimizing changes to operational air refueling procedures and minimizing modifications to the current tanker fleet (reference 6).

For the UAV to accomplish a successful refueling rendezvous, the vehicle must be able to safely intercept the tanker, fly formation in the contact position, and egress from the tanker. AFRL has identified several different rendezvous communication architectures (reference 1). The architecture specific to this test program was one in which the UAV was completely autonomous and had no form of communication or data-link to aid in completing the rendezvous. Additionally, the only type of rendezvous considered during this test was a fighter turn-on rendezvous as defined by reference 3, and 4. Although other communication architectures and rejoin types were possible, the scope of the test was a limited evaluation of an autonomous fighter turn-on rendezvous.

A major challenge of the autonomous fighter turn-on rendezvous was to develop a UAV guidance system to support safe, autonomous rejoin. Central to this challenge were the sensors required to detect and track the tanker and provide guidance information for the UAV during rendezvous. These sensors had to meet basic performance requirements, but were also subject to other constraints: low observable UAV designs restricted potential viewing angles; the safety of tanker personnel during refueling limits transmission power of active systems; and, limited UAV maneuver performance added difficulty in completing a rendezvous. Examining potential rejoin scenarios to determine required UAV sensor field-of-regard and minimum detection range was desired to aid in identifying satisfactory sensor technologies.

USAF TPS Class 03A conducted the MEDIUM RARE test to support UAV sensor trade studies as part of AAR. In particular, this flight test program focused only on the segment of air refueling operations from initial detection of the tanker aircraft by the UAV through rendezvous to the arrival of the UAV in trail approximately 1 NM behind the tanker.

## TEST ITEM DESCRIPTION

The test item was the rendezvous procedure used to determine sensor range and field-of-regard requirements. Current fighter turn-on maneuvers were used as a pattern to design the procedure. This procedure is detailed in Appendices A and B.

## TEST OBJECTIVES

The overall objective was to determine sensor field-of-regard and detection range requirements for a UAV to accomplish an autonomous fighter turn-on air refueling rendezvous. There were two specific test objectives: to determine the required sensor detection range for a successful rendezvous given an initial aspect angle and sensor field-of-regard, and to evaluate the operational utility of the UAV turn-on procedures. All test objectives were met.

# TEST AND EVALUATION

Prior to testing, no specific unmanned air vehicle (UAV) rendezvous procedures existed. Therefore, to determine sensor performance parameters, rendezvous procedures were developed that emulated current fighter turn-on procedures.

An algorithm was implemented in MATLAB® to develop turn-on procedures and to analytically predict required sensor detection range for a given aspect angle and sensor field-of-regard (FOR). Air Force Research Laboratory (AFRL) provided a D-6 flight simulator with autopilot capability, and the same turn-on procedures developed in MATLAB® were programmed into the D-6 simulator. The D-6 simulator was run for a subset of the MATLAB® simulated conditions to verify the analytical predictions. Flight test data were collected on this same subset of conditions to spot check the simulation and increase confidence in the analytical results. Two F-16B aircraft were used to simulate UAV and tanker roles and complete flight testing.

The combination of simulation and flight test resulted in successful completion of the test objectives. Required sensor detection range for each FOR was determined, and operational utility comments on the UAV rendezvous and procedures were collected.

## SENSOR DETECTION RANGE FOR SUCCESSFUL RENDEZVOUS

### Rendezvous success criteria

The first objective was to determine the required sensor detection range for a successful rendezvous given an initial aspect angle and sensor field-of-regard. For the purposes of this discussion, required sensor detection range was defined as the minimum UAV-to-tanker range that allowed the UAV to initiate and successfully complete a rendezvous. For a rendezvous to be considered successful, four criteria had to be met. These criteria served as the basis for evaluating both simulation and flight test results and are described below.

#### UAV-to-Tanker Range

UAV-to-tanker range was considered satisfactory if the tanker remained within the maximum detection range of the UAV sensor configuration under test throughout the rendezvous.

#### Tanker Safety Separation

UAV separation from the tanker was considered satisfactory if the UAV maintained a minimum of 1000 ft of vertical separation below the tanker aircraft's altitude, and 4000 ft of lateral separation from the tanker aircraft during the rendezvous.

#### End Game

The end game was considered satisfactory if the UAV range from the tanker was 0.7 to 3 NM, with a tanker aspect angle between 20° left and 20° right (Figure 1), and a final heading within 20° of the tanker heading.

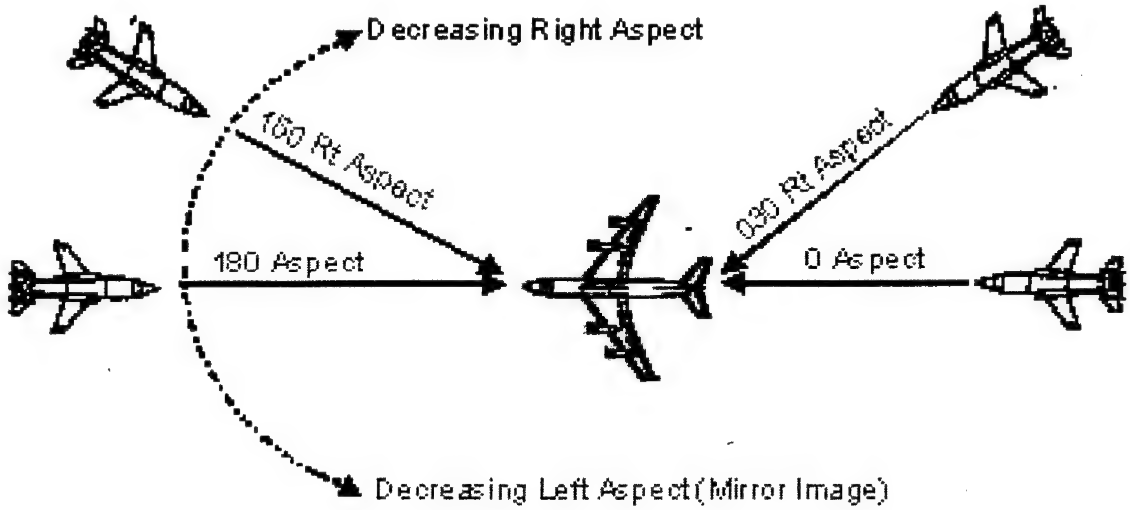


Figure 1. Aspect Angle Definition

UAV-to-tanker Line-of-Sight

The line-of-sight (LOS) from the UAV to the tanker was considered satisfactory if the rendezvous was flown within the FOR of the sensor configuration under test throughout the maneuver. The LOS, or total off bore-sight angle, was also decomposed into azimuth and elevation angles, as depicted in Figure 2. Figure 2 depicts a sensor with azimuth and elevation FOR limits of ±90°. These angles were measured with respect to the body axis system of the UAV. AFRL proposed several candidate sensors as shown in Appendix C. Of these, none had a "look-down" capability due to airframe design constraints. Thus, the time that the elevation was negative (shaded region in Figure 2) was tracked as a critical parameter. The only time a negative elevation angle was considered acceptable was during the opening turn when negative elevation angles were unavoidable.

**Test Procedure**

To establish UAV rendezvous procedures for autonomous air refueling, an event driven algorithm was developed that emulated typical high-aspect, fighter turn-on procedures. This procedure is presented in detail in Appendix A. The algorithm was implemented in MATLAB® code, which used simple point mass dynamics to simulate the rendezvous. The MATLAB® implementation is discussed at length in Appendix B.

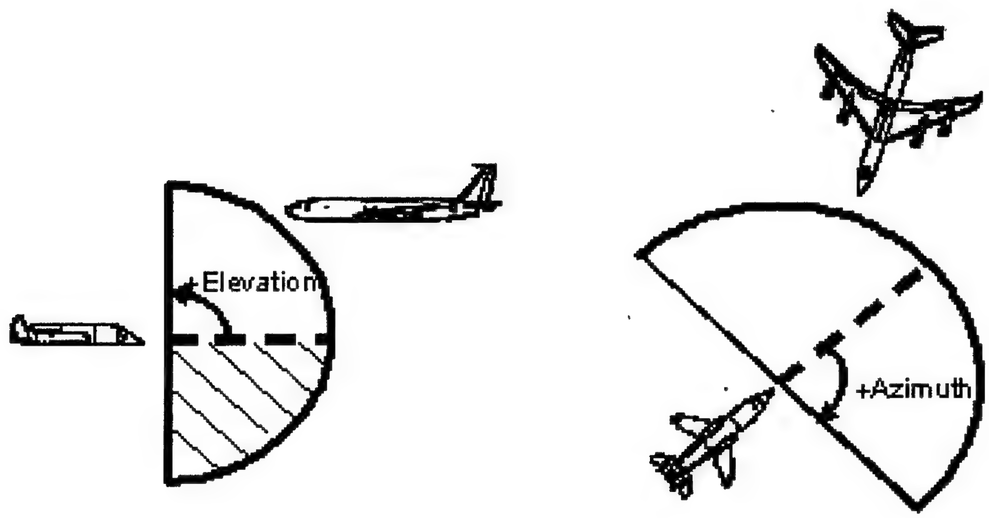


Figure 2. Sensor Field-of-Regard Definition

The four rendezvous success criteria were used to run the algorithm iteratively and evaluate the simulation results to produce the sensor detection range required for each sensor configuration and aspect angle condition. The simulation was based on AFRL estimates of future UAV performance capabilities. A key UAV performance capability was the ability to sustain a 2.5g level turn at 27,000 ft MSL and 445 KTAS. The rendezvous were constrained to constant altitude maneuvering to blend with current operational practices and address safety considerations.

A typical rendezvous is detailed in Figure 3. The maneuver started with a 2.5g opening phase where the UAV turned to gain sufficient cross-track separation from the tanker's flight path. During the opening turn, the UAV banked away from the tanker, resulting in negative elevation angles. Once the UAV opened to its sensor FOR limit, the UAV rolled out and maintained the maximum allowable LOS for the sensor configuration, while continuing to gain cross-track separation. Once the along track range decreased enough and the cross-track separation was sufficient, the UAV began the closing phase, by initiating a 2.5g turn. The closing phase was continued to a point where the UAV could roll out level and fly to a desired end game. The fastest way to reach that end point after rolling out of the closing turn was to fly straight and level and lead the tanker for an ideal intercept 1 NM in trail. This phase was called "cut to intercept."

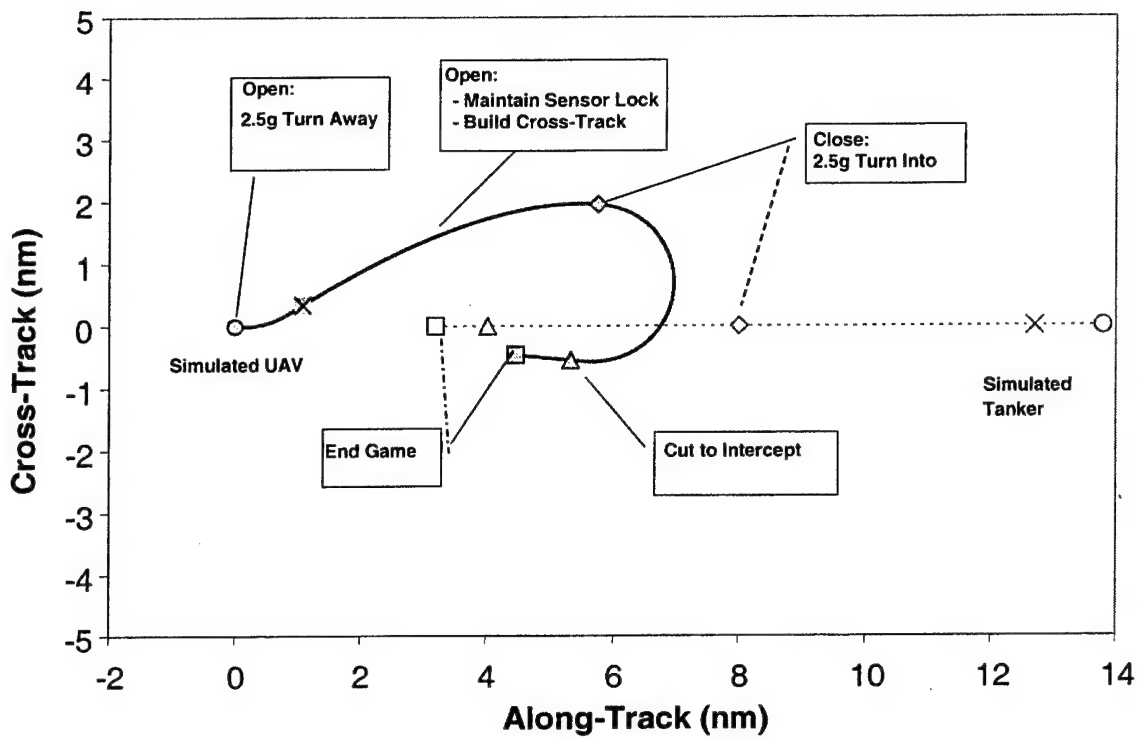


Figure 3. Example Rendezvous from God's Eye View

After completing the iterative MATLAB® simulation runs to analytically determine the minimum allowable sensor detection range, a subset of simulation points (Appendix D) were run using the AFRL provided D-6 flight simulation code. D-6 was used as an intermediate code to provide confidence in the MATLAB® simulations. AFRL incorporated an autopilot into D-6 capable of accepting rendezvous algorithm commands. These rendezvous commands were produced by a C++ implementation of the exact same rendezvous algorithm used in the MATLAB® simulation. The results of the D-6 runs were used to verify the MATLAB® simulation and provide greater confidence in simulated predictions before proceeding to flight test.

To further raise the level of confidence in the full set of simulation results, the same subset of conditions run in D-6 were flight tested using two F-16B aircraft with one aircraft acting as the UAV and the other one playing the role of the tanker. The flight test points emphasized high-aspect angle rendezvous conditions, as they were the most aggressive maneuvers and stressed range and LOS limits. Simulation results were used to provide range and aspect angle data for the open, close, and end game points during each maneuver, which allowed the aircrew to emulate the decisions the rendezvous algorithm would make during each rendezvous. The fire control radars in both F-16Bs were used to monitor tanker range and aspect angle throughout the maneuver. The radar tracks provided cues for maneuvering at the predetermined open, close, and end points. Throughout the rendezvous, time, space, position information (TSPI) data were collected for both aircraft.

Flight test focused on two specific sensor configurations that were evaluated during simulation (Appendix C). AFRL identified the ±90° FOR and the ±40° azimuth / ±70° elevation FOR sensor configurations as priority cases. Thus, flight test and D-6 data were collected on those two configurations, while the only data produced for the remaining cases were generated using the MATLAB® simulation.

Flight test tolerances were set to ±0.2 g, ±10 KCAS, ±0.2 NM range, ±5° heading, and ±5° aspect angle. Tight tolerances were required to effectively replicate the rendezvous procedures. To directly assess the effectiveness of the simulation against flight test results, the simulation was run with identical conditions to those encountered during flight test. These comparisons are presented in Appendix F. This approach allowed for a closer comparison of the flight test and simulation results, as shown in Appendix G.

## Test Results

### MATLAB® Simulation

The simulation was run for symmetrical, conical sensors with FORs of ±90°, ±80°, ±70°, ±60°, ±50°, ±40°, and ±30°, and one asymmetric (±40° azimuth by ±70° elevation) sensor. Each FOR was run for initial tanker aspects ranging from 180° to 90° with the tanker flying straight-and-level, as well as three conditions in which the tanker maneuvered in level, constant airspeed, 20° turns. These three maneuvering conditions were: the tanker turning at the UAV opening point; the tanker turning away from the UAV at the closing point; and the tanker turning toward the UAV at the closing point. In all three cases, the tanker held the established turn until completion of the rendezvous.

Simulation results for a subset of the tested configurations are shown in Figure 4. The figure shows the variation of required detection range for five different sensor FOR configurations as tanker aspect angle was varied. As expected, higher aspect angles and smaller FORs required a much greater sensor range to successfully complete tanker rendezvous. Yet, required sensor range was not just a function of sensor FOR and rendezvous geometry but was also a function of the UAV's maneuverability. In general, turn capability and sensor FOR were the primary drivers in determining required sensor detection range. Simulation results are provided in Appendix C.

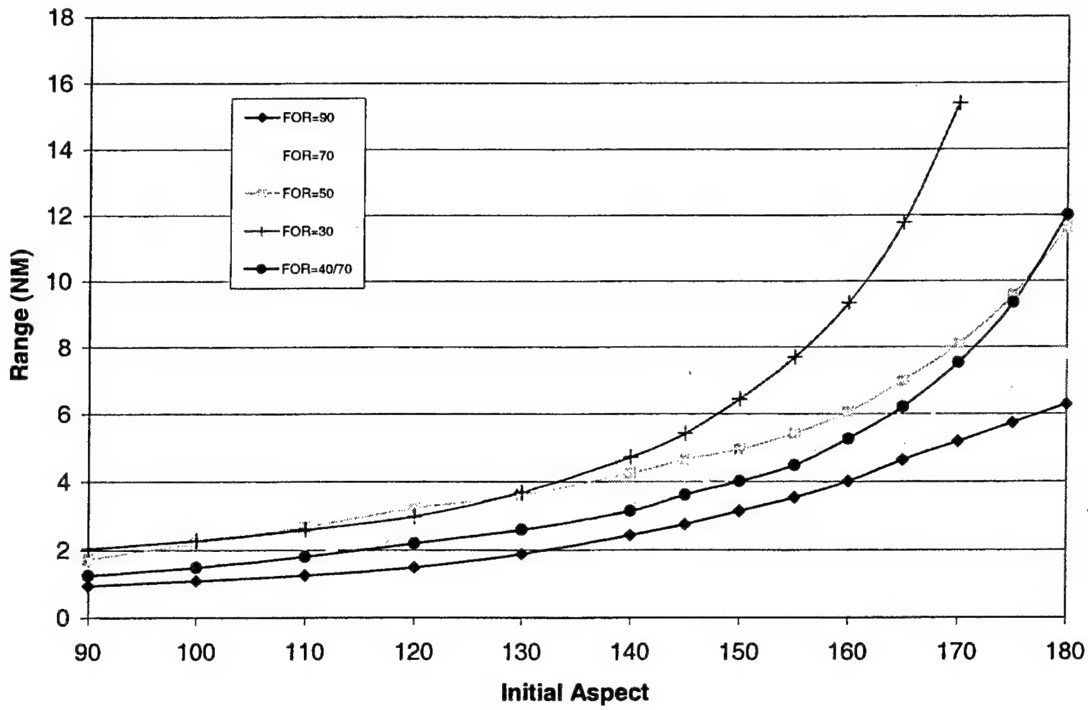


Figure 4. MATLAB® Simulation Results: Required Range versus Aspect Angle

A limited number of cases with a maneuvering tanker were analyzed for each sensor configuration. These results are also presented in Appendix C. For these cases, if the tanker turned at the opening point or turned away at the closing point, a successful rendezvous could still be accomplished in the same range as required for a non-maneuvering tanker. However, at the same range, the rendezvous would fail if the tanker turned toward the UAV when it was at its closing point. Despite the small number of cases analyzed, the effects of tanker maneuvering were apparent and significant. If the tanker turned away from the UAV during the rendezvous, the required range would decrease, but if the tanker turned toward the UAV, the required range would increase. Without any way to ensure the tanker would never maneuver toward the UAV, the minimum range would have to be for the worst case—the tanker turning toward the UAV. Minimizing tanker maneuvering during rendezvous would decrease the required detection range.

Maneuvering is an operational necessity for a tanker and may not be avoidable during UAV rendezvous. Therefore, many more tanker maneuvering cases should be investigated to further assess the impact of tanker maneuvering on the rendezvous. Higher bank angles, maneuvering at different times during the rendezvous, various levels of tanker position, velocity, and heading knowledge are all key considerations that were not addressed in this analysis, and the full effects of maneuvering on rendezvous success should be understood before establishing minimum ranges and procedures for

rendezvous. **Further investigate the impacts of tanker maneuvering on UAV rendezvous success (R1).**[1]

Simulation with a maneuvering tanker uncovered a limitation in the rendezvous procedure. Because opening negative LOS had been accepted as unavoidable and non-maneuvering tanker rendezvous geometry did not produce negative LOS elevation during rendezvous, the rendezvous procedure did not incorporate any logic to avoid generating a negative LOS elevation. The procedure, instead, assumed the sensor was a full conical sensor to simplify the calculations. However, this simplification caused problems when the procedure was implemented against a maneuvering tanker. For the sensor with 90° FOR and the tanker turning away at the UAV opening point (Intercept 10 in Appendix F), the rendezvous procedure commanded a profile that generated negative LOS elevation during the cut-to-intercept and caused the maneuver to fail the rendezvous success criteria. In order to utilize the rendezvous procedure against a maneuvering tanker, a change to the procedure was implemented during flight test, but it was not integrated into the MATLAB® simulation or rendezvous procedure. **Modify the rendezvous procedures to avoid negative line-of-sight elevations with regard to a maneuvering tanker (R2).**

D-6 Simulation

Upon completion of the simulation runs to determine the required sensor detection range for each sensor FOR, flight simulation was conducted on a subset of the simulation cases using the AFRL D-6 flight simulator. The results were used to verify the MATLAB® implementation of the rendezvous algorithm. Appendix D defines the subset of sensor configurations and aspect angles that were run in the D-6 flight simulation. Appendix E presents all D-6 results.

[1] Numerals preceded by an R within parentheses at the end of a paragraph correspond to the recommendation numbers tabulated in the Conclusions and Recommendations section of this report.

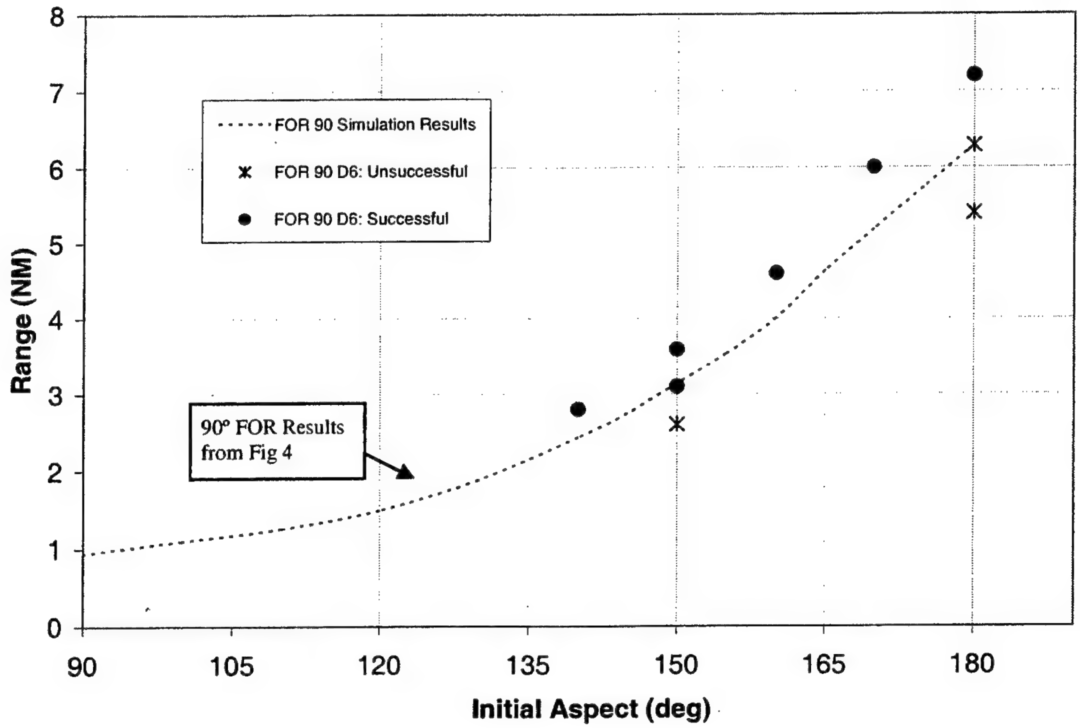


Figure 5. D-6 Results: Required Range versus Aspect, 90° Sensor

Figure 5 presents the comparison of the D-6 and MATLAB® simulation results for the ±90° FOR sensor configuration. Multiple aspects were investigated at the MATLAB® predicted minimum range plus 15%, and all cases generated successful rendezvous. For aspect angles of 150° and 180°, runs were also performed at the minimum range and minimum range minus 15%. At points of minimum range minus 15%, the rendezvous were unsuccessful, as expected. At the minimum range points, the 150° aspect was successful, but the 180° aspect was not. The difference at the 180° initial aspect point between D-6 and MATLAB® simulation highlighted the impact of autopilot performance. Using the autopilot in D-6 to drive the rendezvous resulted in g overshoots and undershoots of the rendezvous commands that differed from the "perfect autopilot" in the MATLAB® simulation. The variation in the g-command tracking performance showed that using the actual UAV autopilot to determine the required detection range will be essential in future testing. **Validate rendezvous success and sensor requirements using production representative UAV autopilot (R3).**

Flight Test

Due to the tight flight test tolerances necessary to execute rendezvous, only 19 of 52 rendezvous attempts were flown within test tolerances by the aircrew. These tolerances are presented in Appendix F. Flights were accomplished in the Isabella military operating area with altitudes ranging from 20,000 to 28,000 feet pressure altitude. True airspeed was held constant at 445 KTAS for the UAV and 417 KTAS for the tanker to accurately simulate 275 KCAS at 28,000 ft and 300 KCAS at 27,000 ft on a

standard day for the tanker and UAV, respectively. The two sensor configurations tested during flight were ±90° FOR and ±40°/±70° FOR.

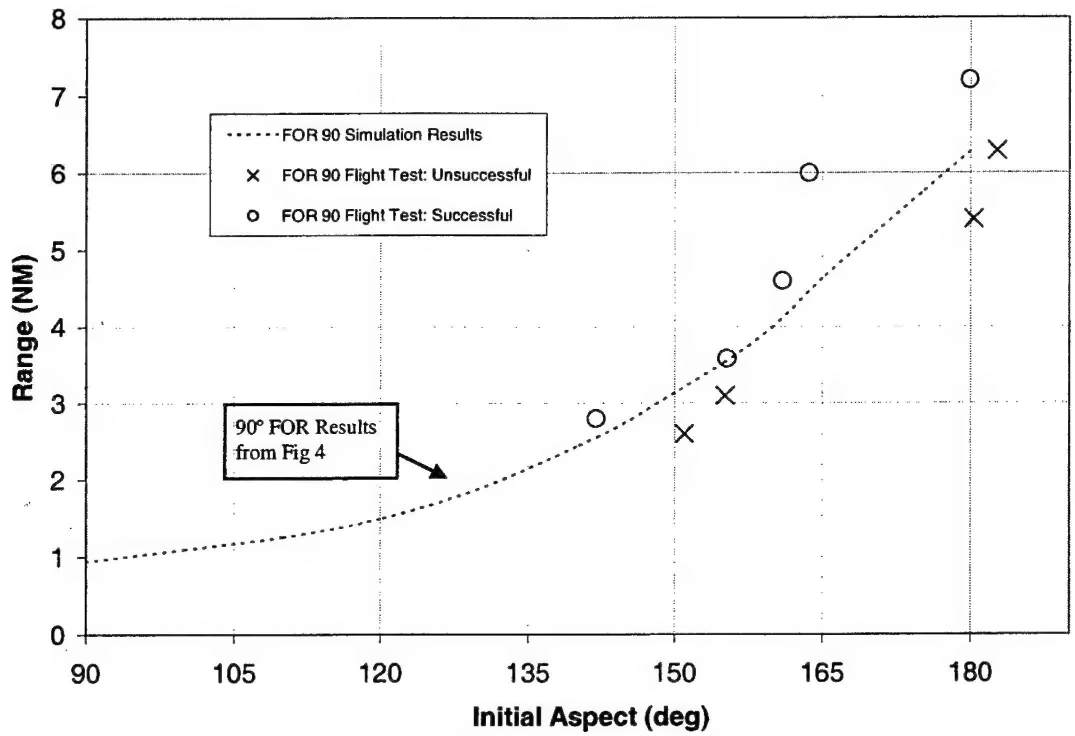


Figure 6. Flight Test Results: Required Range versus Aspect Angle, 90° Sensor

Flight test results followed predicted simulation trends. Figure 6 presents the ±90° sensor configuration flight test results compared to the simulation results. Complete results for each flight test point are presented in Appendix F. Appendix G provides all the result graphs, including results for the ±40°/±70° sensor configuration.

All flight test points performed above the predicted allowable detection range were successful. Flight test points flown below the minimum range were unsuccessful due to either excessive LOS to the tanker or incursions of the tanker "safety zone". These results were consistent with simulation predictions. The correlation of predicted and flight test results provided a high level of confidence in the predicted minimum range. The results for the ±40°/±70° sensor configuration supported the same conclusion. The required range for each sensor was based on the 180° aspect angle requirement, which had the largest required detection range for each sensor. The required sensor detection ranges for a perfectly executed maneuver against a non-maneuvering tanker are provided in Table 1. It is important to note that the results presented are the minimum range to begin the rendezvous procedure and do not take into account any time required to acquire and build track files on the tanker and do not include a buffer to account for additional uncertainties.

Table 1. Flight Test Results: Minimum Range versus Initial Aspect Angle

| FOR | **±90°** | **±80°** | **±70°** | **±60°** | **±50°** | **±40°** | **±30°** | **±40°/±70°** |
|---|---|---|---|---|---|---|---|---|
| Range* (nm) | 6.3 | 6.9 | 7.8 | 9.2 | 11.6 | 16.8 | > 20.0 | 12.0 |

* Range values are the analytical minimums and do not include any margin for error

Flight test results were also attained for two of the maneuvering tanker cases presented in Appendix D. Intercept 10 demonstrated that the slight modification to the cut-to-intercept portion of the rendezvous procedure successfully reduced the negative line-of-sight elevation from 35 seconds to 0 seconds during the cut-to-intercept phase. The modification entailed leveling off after the closing phase and allowing the tanker to pass in front of the UAV before beginning a cut-to-intercept maneuver. The simulation procedure, on the other hand, did not level before beginning the cut-to-intercept, and executed a gentle turn inside the tanker to reach 1 NM in trail. Figure 7, shows the difference between the simulation and flight test position tracks. The complete comparison of results is presented in Appendix F. These flight test points demonstrated that a successful rendezvous procedure for the maneuvering tanker scenario existed. However, the further efforts to fully develop those procedures and implement them into the MATLAB® simulation were not accomplished. The operational impact of the different maneuvers will be addressed as part of the operational utility discussion.

It cannot be overemphasized that the results for minimum required sensor range were created based on a set of assumptions provided by AFRL that related to sensor performance, UAV maneuvering performance, and rendezvous parameters. These results pertain only to a single design point, a UAV flying 445 KTAS at 27,000 ft and a tanker flying 417 KTAS at 28,000 ft. Additionally, rendezvous success was predicted at these ranges using a simulation that incorporated perfect tracking of autopilot commands. These assumptions, their relation to the operational environment and the influence of changes to them must be taken into account when assessing the validity of the results. During flight test, a buffer of 15% was added to many test point minimum ranges in an attempt to ensure successful rendezvous in spite of small deviations from the above assumptions. For rendezvous with "cold aspects", 150° aspect angle or less, the 15% buffer was adequate, and flight within test tolerances produced successful rendezvous. In fact at 150° aspect, the 15% buffer was excessive, allowing errors that exceeded flight test tolerances to produce successful rendezvous. For aspect angles higher than 150°, the 15% buffer was inadequate. Flight test results suggest a buffer of greater than 15% at high-aspect angles and less than 15% at aspects below 150°. Actual minimum range values should include a range buffer in addition to the analytically predicted required range to account for rendezvous errors and disturbances. The buffer was a function of many parameters but was strongly influenced by initial aspect conditions. **Add a buffer to the minimum sensor range based on rendezvous parameter sensitivity testing (R4).**

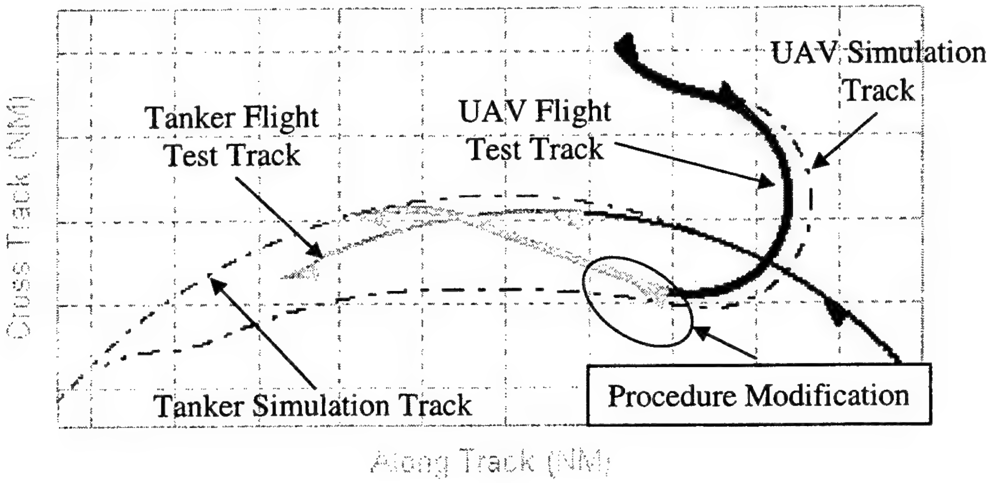


Figure 7. Intercept 10: Comparison of Simulation and Flight Test Tracks

## OPERATIONAL UTILITY

Minimum sensor detection range and sensor FOR were technical drivers for the implementation of a totally autonomous UAV air refueling rendezvous architecture. The operational utility of autonomous air refueling was driven not just from the sensor technology but from the procedures utilized to rendezvous. Research of current fighter turn-on procedures, analysis of the simulated data, as well as pilot comments collected after each rendezvous were compiled to provide an operational utility assessment of the UAV rendezvous, as executed. This assessment was composed of two primary areas: air refueling mission impacts and autonomous rendezvous design considerations.

### Autonomous Rendezvous Air Refueling Mission Impacts

Four major mission impacts for air refueling were identified. Those were the compatibility of autonomous rendezvous with current operational procedures, safe separation of the UAV from the tanker during the turn-on procedure, sensor FOR limitations on rendezvous procedures, and UAV maneuver limitations.

Rendezvous Compatibility

The rendezvous procedures tested resembled current fighter turn-on procedures. The procedure dictated rendezvous geometry similar to what a pilot would execute during a visual rejoin. The close maneuvering at the minimum required detection range made the procedure appear more aggressive than standard from the tanker perspective, but maneuvering was not out-of-the-ordinary or considered objectionable. Hence, the position and maneuvering of a UAV performing the autonomous rendezvous procedures should appear like normal operations to the tanker pilot.

There was one exception where the rendezvous procedure flown did not resemble current tanker rejoins. In the case of a maneuvering tanker previously described, Figure 7, the UAV procedure flown entailed leveling off after the closing phase and allowing the tanker to cross the UAV flight path from right to left before beginning a cut-to-intercept maneuver. This approach allowed the UAV to keep sensor line-of-sight positive and within FOR limits, but was considered non-standard because it resulted in the UAV overshooting the tanker's flight path. As flown, the procedure could potentially lead to more aggressive situations in which the tanker and UAV flight paths cross at closer ranges and higher aspects. A more standard response would have been to execute a gentle turn inside the tanker turn radius to reach 1 NM in trail as shown in the UAV simulation track in Figure 7.

<u>Safety Separation</u>

Tanker safety separation rendezvous success criteria was implemented to establish an operationally representative UAV keep-out zone (4,000 ft horizontal and 1,000 ft vertical separation from the tanker). This safety zone is shown in Figure 8 as the solid colored circle. Safety zone incursions occurred primarily during rendezvous with large FOR sensors. The large FOR sensors allowed the UAV to maneuver at closer ranges without exceeding sensor FOR. During flight test, there was an increased probability of safety zone incursions with the ±90° FOR sensor. Even though the rendezvous were predicted to pass outside the safety zone, small deviations from the procedure during pilot execution resulted in incursions.

Pilot comments from flight test revealed that a circular, 4,000 ft horizontal separation was inadequate from the tanker pilot perspective. Comparison of pilot comments from intercepts that passed within 4,000 ft to 6,000 ft of the tanker supported an increased safety zone range to the sides and rear of the tanker to approximately 1NM. For forward separation, intercepts with the UAV maneuvering within 2.5NM in front of the tanker were considered objectionable to the pilot in the tanker. Separation during other intercepts was considered adequate where maneuvering in front of the tanker occurred outside 3NM. Additionally, research into operational safety zones of other aircraft revealed that typical safety zones were defined with different ranges to the front, sides, and rear of the tanker to account for large differences in closure velocity. An elliptically shaped safety zone was considered more operationally representative and is shown in Figure 8 as the larger, stripped region. Flight test data suggests safety zone dimensions of 1 NM to the sides and rear, and 3 NM in front of the tanker. **Implement an elliptical UAV keep-out zone (with the greatest distance being in the along-track direction and in front of the tanker) while maintaining an altitude separation of greater than 1,000 ft until the UAV is behind the tanker (R5).**

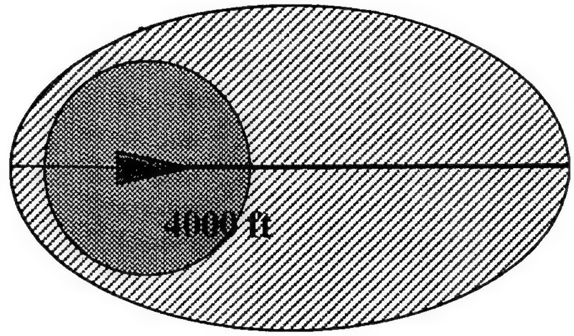


Figure 8. Tanker Safety Zone

Sensor Line-of-Sight

An important criterion in assessing the success of a rendezvous was the requirement for the UAV-to-tanker line-of-sight to remain within the sensor FOR. For the UAV, exceeding the sensor FOR would translate into periods of time that the UAV sensor could not detect or update track information on the tanker. Loss of sensor LOS with the tanker, therefore, violated the rendezvous procedure assumption, in which the UAV had perfect knowledge of the tanker position and velocity. The lone exception to this criterion was the opening phase where the UAV had to turn away from the tanker to initiate the rendezvous. This period of negative LOS elevation was viewed as unavoidable. Although the amount of time the LOS elevation was negative was tracked, this information was not used to assess rendezvous success. Rather, AFRL was interested in tracking these times to understand sensor coverage capabilities (reference 1).

Except for the initial opening phase of the rendezvous, UAV-to-tanker LOS was required to remain within sensor FOR limits for rendezvous success. This assumption was potentially too stringent. Momentary losses of elevation or azimuth coverage could be handled in UAV control algorithms by propagating the last known position and velocity of the tanker over the short period of time. This technique would be similar to methods used by current fire control radars that keep aircraft track files propagating after losing a return signal for several time frames before dropping track. An example would be an air-to-air radar that was tracking a threat aircraft into the notch. Modern radars employ techniques to predict where the threat would be if it had continued flying unchanged from the last update and search for the threat near that prediction to regain sensor lock.

For Intercept 18 shown in Appendix F, UAV-to-tanker LOS remained within the sensor FOR for the entire rendezvous except for a 1.5 second time period when the LOS exceeded the azimuth limit. A time history of this rendezvous LOS azimuth and elevation angles and UAV bank angle are shown in shown in Figure 9. If short drops in sensor coverage had been allowed, the rendezvous would have been successful. The data point for this rendezvous is shown as the triangle in Figure 10. Momentary drops in sensor coverage due to exceeding sensor field-of-regard should be acceptable and accounted for by the UAV rendezvous control algorithms. **Investigate the impacts of momentary loss of sensor coverage, utilizing actual UAV rendezvous procedures and safety criteria (R6).**

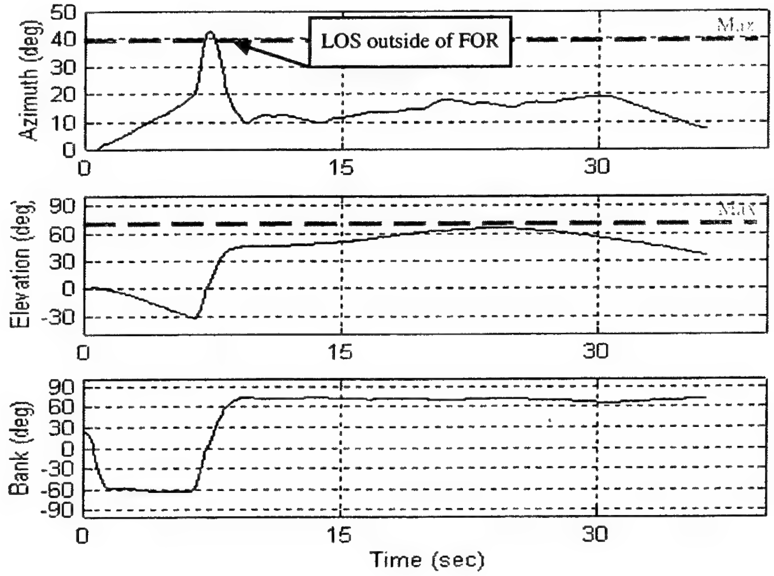


Figure 9. Line-of-Sight Time History for Intercept #18

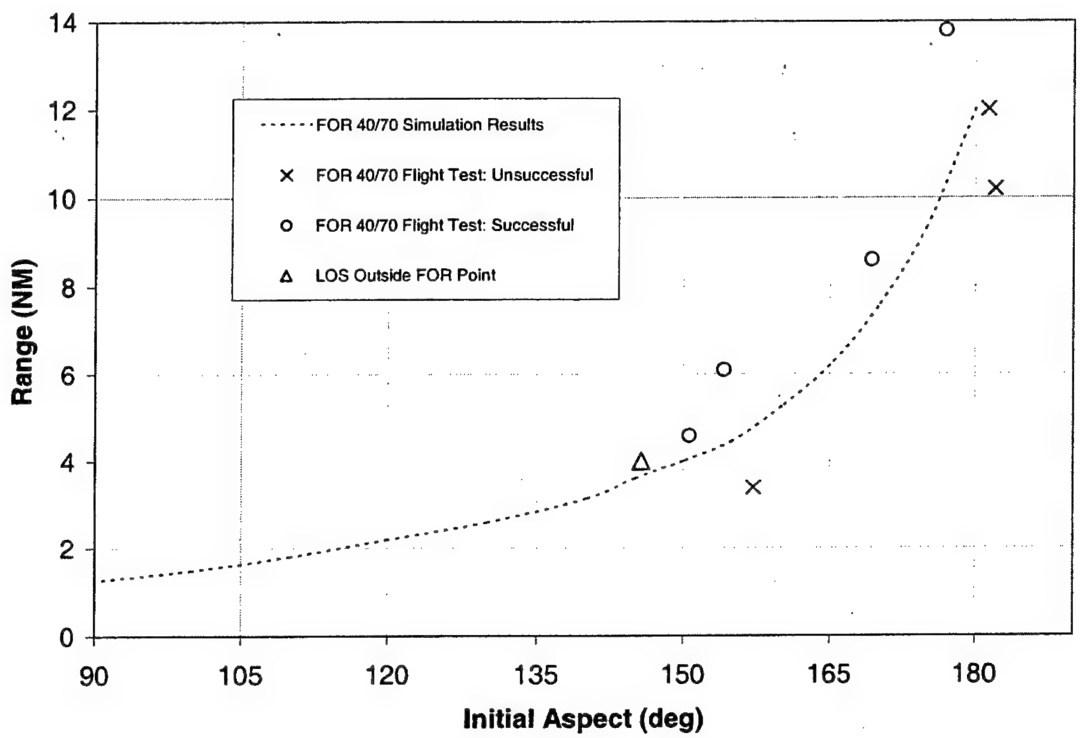


Figure 10. Momentary Sensor Coverage Drop Comparison

In the event that a drop in sensor coverage becomes extended, or the rendezvous is determined to be unsuccessful for any reason by the UAV, the UAV will need to have a preplanned abort procedure to ensure the UAV and tanker can safely separate. Abort procedures where not addressed as part of the program, but will be a critical safety consideration in the future. **Develop UAV abort procedures to be implemented when an unsuccessful rendezvous occurs (R7).**

UAV Maneuver Limitations

For the rendezvous procedures, the UAV was limited to constant airspeed, constant altitude maneuvering. Additionally, maximum roll rate was limited to 40°/s and the maximum turn rate was limited by the maximum sustainable g of 2.5g. These limitations directly shaped the rendezvous geometry. Changing these limitations has both positive and negative impacts on the rendezvous. For example, increasing airspeed during the opening phase to gain cross-track, decreasing airspeed in the closing phase to reduce turn radius, and increasing airspeed during the cut-to-intercept phases of the rendezvous could reduce the required detection range and the duration of the rendezvous. Maneuvering to the maximum instantaneous g versus maximum sustainable g at specific points during the closing phase could help eliminate LOS excursions outside the sensor FOR. Maneuvering at maximum instantaneous g does imply that the maneuver would lose energy, and changes in energy should be considered carefully. Maneuvering in the vertical or at maximum instantaneous g would not only increase rendezvous complexity, but also raise safety concerns. Varying altitude rendezvous would be less predictable, as well as have impacts on rendezvous of UAV formations or blending with other aircraft in tow behind the tanker. Utilizing constant altitude turn-on procedures for future UAV designs would avoid these negative impacts.

## Autonomous Rendezvous Design Considerations

Research of current fighter turn-on procedures, analysis of simulated data, and pilot comments collected after each rendezvous were compiled to provide observations on the rendezvous procedures and design considerations for future UAV autonomous procedures.

Rendezvous Procedures

The most common cause of unsuccessful rendezvous was UAV-to-tanker LOS exceeding FOR limitations. As previously recommended, adding additional range buffer by increasing sensor performance or increasing the range for initiating the opening turn would allow the UAV to maneuver less aggressively and reduce the potential for LOS excursion outside sensor FOR.

UAV-to-tanker LOS excursions outside the sensor FOR occurred primarily during the opening and closing phases. FOR excursion also occurred during the cut-to-intercept phase during rendezvous with a maneuvering tanker.

During the opening phase, the UAV turned away from the tanker to establish cross-track. This resulted in an intentional and unavoidable negative LOS elevation, and

because the UAV had no look-down capability, the UAV had no sensor coverage. Intercept 1 (flight 1) in Appendix F shows the UAV was blind for the first 10.5 seconds of the maneuver, which was an excessive amount of time to go without sensor coverage considering the closure velocity of greater than 800 KTAS. Lower aspect angle intercepts helped to reduce time with negative elevation because the opening turn required a shorter opening turn. Comparing Intercept 2 to Intercept 7 (flight 1) in Appendix F, negative LOS elevation time was reduced from 13 seconds at a 180° aspect to 3.7 seconds at a 150° aspect. Negative elevation angle also occurred when the UAV turned inside the tanker's turn radius (Intercept 10 MATLAB® simulation). Negative elevation angle could also result from high positive angle-of-attack flight or altitude deviations during rendezvous, which place the sensor's zero elevation line above the tanker. Because negative elevation angles are easily encountered and nearly unavoidable, the UAV will need some degree of look-down capability to prevent sensor coverage loss. **Investigate sensor suites with a look-down sensor capability (R8).**

To prevent unintentional LOS excursions during the opening phase a buffer was added to the maximum commanded UAV-to-tanker LOS generated by the rendezvous algorithm. The control algorithm utilized an empirically determined 7° or 14° buffer depending on the rate of change of LOS to accommodate overshoots in LOS that occurred during opening. For example, Intercept 13 in Appendix F shows an aggressive pull to ~ 33° (azimuth limit was 40°) was accomplished during the first 8 seconds, and the UAV was able to keep the LOS 33° off bore sight throughout the remainder of the opening phase (the next 45 seconds). Since the UAV had control over the LOS, the tanker remained within the sensor FOR throughout the opening. Without the implementation of a small buffer on the elevation or azimuth LOS limits many rendezvous known to be successful resulted in failure.

In order for the UAV to be able to control the LOS, the angular rates between the UAV and tanker had to be significantly lower than the UAV turn rate. Although angular rates could impact the opening phase of the rendezvous, the closing phase was typically where rates were most important. The rendezvous procedure used along-track distance to determine where to initiate the closing turn. This point was the point where the turn radius permitted the UAV to roll out of the turn a desired distance behind the tanker. However, once the close was initiated, the short range and relative position between the two aircraft created a large LOS rate of change. With poor geometry, the LOS rate of change could exceed the UAV's maximum turn rate, and lead to an uncontrollable LOS excursion over the LOS limit. As the UAV was already at the maximum turn capability during this phase, the autopilot/pilot did not have direct control over this excursion. The only way to avoid the LOS excursion was to create a more favorable geometry for the closing phase during the opening phase.

Favorable geometry was created by having the proper along-track distance while simultaneously having enough cross-track separation at the start of the closing point. Cross-track separation of the UAV from the tanker was a combination of the cross-track due to initial aspect angle and cross-track gained during the opening phase. As an example, Intercept 13 had negligible initial cross-track, and during the opening phase a cross-track of 1.5 nm was built. This cross-track was insufficient and caused a LOS

spike of 84.9° during the closing phase. Test results indicate that for a sensor with a 40° by 70° FOR a successful rendezvous could be accomplished with 1.9 nm or greater cross-track (refer to Intercepts 11-21, Appendix F). Results were similar for a sensor with 90° FOR with cross-track of 1.5 nm or greater resulting in successful intercepts (refer to Intercepts 1-10, Appendix F). Test data also indicated that deviation in cross-track distance had a much more significant impact than deviation in the along-track distance when initiating the closing turn. Therefore, future UAV rendezvous algorithms should emphasize establishing adequate cross-track prior to the closing phase. With planning, the cross-track separation could be achieved with less maneuvering by establishing a good initial aspect between the UAV and tanker, rather than performing a high-g opening turn. For a 2.5g maneuvering UAV having 2 nm of cross-track prior to closing should allow for a successful rendezvous. **To aid rendezvous geometry, A UAV should plan to rendezvous with an offset to the tanker track to provide initial cross-track separation (R9).**

Sensor Design Trades

Sensor design tradeoffs were also identified. First, larger sensor FOR directly correlated to shorter required ranges, (see Table 1). This was a direct consequence of the UAV being able to aggressively open at greater LOS angles to achieve adequate cross-track distance. A good example is seen when comparing the LOS time histories of Intercept 1 and 13 in Appendix F.

Another important tradeoff was between the size of azimuth and elevation limits in the sensor FOR. As seen in Intercept 18 in Appendix F, approximately 9 seconds into the rendezvous the rollout from the opening turn was performed. During the max rate rollout, the change in elevation LOS was close to 70° while the change in azimuth was 18° to 42°. After the closing phase, the azimuth LOS remained about 20°, while the elevation LOS was near the sensor limit of 60°-70°. The point at which the UAV rolled out of the initial opening pull was primarily dictated by the most restrictive sensor limit; therefore during this rollout, both azimuth and elevation were equally important. During the closing phase of the rendezvous, the elevation component of the FOR was the most dominating parameter.

Other key issues in the sensor design were outside the scope of this test, but they are worth briefly mentioning as it became apparent during testing that they will have significant impact on the operational utility of autonomous rendezvous. Those issues revolved around how and if the UAV would be able to discriminate the tanker from other aircraft when multiple aircraft were in its sensor FOR, in addition to the ability of the sensor to discriminate the tanker from clutter in various background environments and weather conditions. Also of importance was exactly how the architecture of autonomous rendezvous would be implemented. The architecture test did not incorporate any form of communication between the UAV and tanker. To fully understand the required detection range and sensor performance requirements, levels of limited communication between the tanker and the UAV should also be investigated. Providing for a small amount of data transfer was expected to mitigate many concerns with LOS control, tanker maneuvering during rendezvous, and tanker identification.

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# CONCLUSIONS AND RECOMMENDATIONS

The objectives of this test were to determine the required sensor detection range for a UAV to autonomously rendezvous with a tanker and to provide an operational utility assessment of the autonomous rendezvous procedures. All objectives were met. Over 3000 different UAV-to-tanker rendezvous cases were simulated, and 19 of those cases were successfully executed in flight to spot check simulation results. These simulation and flight test data were collected and provided to AFRL to assist sensor requirement trade studies.

To determine the minimum sensor detection range for many different sensor configurations a MATLAB® simulation was developed. D-6 flight simulation and flight test data were collected for a subset of the total number of rendezvous cases and verified the predicted minimum detection range. Flight test points initiating rendezvous outside the predicted minimum detection range were successful, while rendezvous started inside the minimum range were unsuccessful. Failure of rendezvous was due to either the UAV-to-tanker line-of-sight (LOS) exceeding the sensor's field-of-regard or UAV incursions of the tanker safety zone. The correlation of simulation and flight test results provided a high level of confidence in the predicted minimum sensor detection ranges for autonomous air refueling rendezvous.

The following discussion presents recommendations in order of priority:

Two recommendations were made that relate to safety aspects of the autonomous air refueling. These two recommendations were:

> **R7: Develop UAV abort procedures to be implemented when an unsuccessful rendezvous occurs (page 17).**

> **R5: Implement an elliptical UAV keep-out zone (with the greatest distance being in the along-track direction and in front of the tanker) while maintaining an altitude separation of greater than 1,000 ft until the UAV is behind the tanker (page 14).**

The minimum detection ranges were determined for a UAV rendezvous with a non-maneuvering tanker. The ranges derived from the MATLAB® simulation also depended on the UAV autopilot executing the exact commands from the rendezvous procedure. The presence of autopilot errors and disturbances inherent to a real system required that a range buffer be added to the minimum range to make the procedure operationally reliable. The buffer was a function of many things including initial aspect conditions.

> **R4: Add a buffer to the minimum sensor range based on rendezvous parameter sensitivity testing (page 12)**

Furthermore, the capability of the autopilot to track the commands had significant impacts on rendezvous success.

> **R3: Validate rendezvous success and sensor requirements using production representative UAV autopilot (page 10).**

UAV rendezvous procedures were created and optimized in simulation. Using rendezvous simulation results, a reduced set of test points were flown so that the pilot's actions emulated the rendezvous procedure. These procedures worked well and should provide a sound basis for future automated rendezvous. During execution of the rendezvous, it became apparent that the most important parameter to achieving a successful rendezvous was cross-track separation.

> **R9: To aid rendezvous geometry, A UAV should plan to rendezvous with an offset to the tanker track to provide initial cross-track separation (page 19).**

Several observations were made on the impact of autonomous rendezvous on air refueling operations. First, the rendezvous were consistent with current fighter turn-on procedures, and would be predictable and not objectionable to the tanker pilot. Second, adjusting airspeed and utilizing instantaneous g capability during the rendezvous could be beneficial in reducing the required range and provide more robust UAV rendezvous procedures. But, the UAV should be limited to constant altitude maneuvering to reduce rendezvous complexity.

Another observation centered on the requirement for the UAV to maintain sensor coverage with the tanker throughout the entire rendezvous. Because the opening turn always created a negative line-of-sight elevation and none of the sensors investigated had a look-down capability, this requirement was not met.

> **R8: Investigate sensor suites with a look-down sensor capability (page 18).**

Negative line-of-sight elevation also occurred in cases with a maneuvering tanker. The procedures for these cases were adjusted for flight test and successfully completed rendezvous avoiding the negative line-of-sight during the end of the rendezvous.

> **R2: Modify the rendezvous procedures to avoid negative line-of-sight elevations with regard to a maneuvering tanker (page 9).**

Additionally, momentary excursions of the line-of-sight outside sensor field-of-regard limits were viewed as potentially too restrictive. Momentary drops in sensor coverage due to exceeding sensor field-of-regard should be acceptable and accounted for by the UAV rendezvous control algorithms.

> **R6: Investigate the impacts of momentary loss of sensor coverage, utilizing actual UAV rendezvous procedures and safety criteria (page 15).**

Finally, although the rendezvous procedures were tested against cases with a maneuvering tanker, the number of cases was very limited.

**R1: Further investigate the impacts of tanker maneuvering on UAV rendezvous performance (page 9).**

It was possible to conclude that a maneuvering tanker would present a more difficult rendezvous cases and would require higher detection ranges to accomplish a successful rendezvous. Minimizing tanker maneuvering during rendezvous would decrease the required detection range.

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# APPENDIX A: RENDEZVOUS PROCEDURE

Procedures for fighters intercepting a tanker for air refueling required a great deal of pilot compensation and monitoring to complete the intercept and keep the geometry correct. To complete a quick and efficient intercept often required extremely aggressive maneuvering on the part of the fighter, possibly in all three dimensions. This situation was most critical at high-aspect angles. The Autonomous Air Refueling program goal was to demonstrate a turn-on procedure for an unmanned air vehicle (UAV) that was similar to the standard fighter turn-on; however, in the case of a UAV refueling rendezvous, some very fundamental limitations existed.

The first limitation was that a UAV does not possess as large a field-of-regard as the pilot. UAV refueling concepts being tested employed a forward-looking sensor with limited field-of-regard to detect and track the tanker aircraft. This design required the UAV rendezvous procedure to ensure the tanker remained within the sensor field-of-regard during the entire maneuver, or at least aggressively mitigate the time the tanker was out of senor coverage during the turn-on maneuver.

Additionally, the UAV was limited in its maneuvering capability when compared to a typical fighter aircraft. According to AFRL, the UAV was able to maintain a constant altitude and airspeed at 2.5g and 27,000 ft. Additionally, the UAV was only able to achieve a maximum roll rate of 40°/sec. No other UAV specific performance data were provided for this test.

These two limitations drove a very specific and hopefully benign maneuvering strategy; yet, the rendezvous procedure had to accommodate high-aspect angle intercepts that were the most difficult for a fighter turn-on. The procedures implemented were taken from a common phase of flight for different rendezvous scenarios. Whether the tanker was established in a refueling track or inbound to the initial point, or whether the UAV was established in an opposing track with altitude separation or inbound to the initial point, the common phase was defined as the UAV in close proximity to a tanker flying straight and level. Regardless of how the two aircraft achieved the rendezvous setup, it appeared that most scenarios led to a high probability of a high-aspect rejoin. In all, the procedure accommodated high-aspect angles while remaining within the limited flight envelope for the proposed UAV.

The solution to these design constraints and limitations was a multi-step maneuver procedure for the UAV. The first step put the UAV in straight and level, un-accelerated flight outside the detection and tracking range of the UAV sensor suite. The second step occurred once the UAV had the tanker within sensor coverage; the UAV then performed an opening turn to gain lateral offset from the tanker while maintaining sensor coverage. Once the UAV was abeam the tanker, the third step had the UAV turn back toward the tanker to close the lateral separation. Once inside aspect angle of 20°L and 20°R and within 30° of the tanker heading, the UAV made small corrections to align its heading with the tanker in an effort to fly to the short trail position, from which it could approach the pre-contact position. The procedure for moving from the short trail position to the pre-contact and contact positions was not addressed as part of this flight test program.

# APPENDIX B: MATLAB® SIMULATION

A test team built MATLAB® simulation was used to simulate rendezvous procedures at various conditions to predict minimum required sensor range. This appendix describes the simulation engine that propagates the unmanned air vehicle (UAV) and tanker positions through time and space, and details the algorithm that allows the UAV to autonomously maneuver for rendezvous. This algorithm created the rendezvous commands used in simulation and was the basis for the profiles flown during flight test.

**Simulation Engine**

The simulation was a point-mass simulation of the UAV and tanker. Each aircraft was assigned the following properties:

1. X (East) and Y (North) position relative to a (ground) fixed coordinate system (Nautical miles).
2. H - Altitude above sea level (feet).
3. V – True air speed (knots).
4. D - Heading relative to true north (0-359.99 deg).
5. $\phi$ - Bank angle relative to wings level (deg, positive was right wing low).

The simulation initialized both aircraft in straight, level, un-accelerated flight at specified positions, velocities and altitudes. Then, it propagated in small time intervals (set at 0.1sec), calculating the next step's parameters from the current ones. Load factor and turn rate were calculated from the bank angle assuming a level, constant airspeed turn. New headings were computed based on turn rate. Given that $X_{i-1}$ represents previous value and $X_i$ represents current value of any parameter, the following formulas were used (unit conversions and signs for left/right are omitted from the formulas below):

<u>Position:</u>

$$\theta = 180 - D$$
$$X_i = X_{i-1} + V\cos(\theta)dt$$
$$Y_i = Y_{i-1} + V\sin(\theta)dt$$

<u>Heading:</u>

From current bank angle, current g was computed:

$$g = \frac{1}{\cos(\phi)}$$

Next, turn rate – w - was computed:

$$w = \frac{9.8\sqrt{g^2 - 1}}{V}$$

Finally, new heading was calculated:

$$D_i = D_{i-1} + w \cdot dt$$

Bank:

Both airplanes responded to g and heading commands. The UAV was controlled by the intercept algorithm using these commands. Goal heading, goal g and turn direction were the outputs of the algorithm at every time step. The simulation used these commands to calculate the airplane's bank angle in the following manner:

A goal bank angle was computed from the goal g (using the same level, constant airspeed assumption):

$$\phi_{goal} = \arccos\left(\frac{1}{g_{goal}}\right)$$

The simulation rolled the airplane using a constant roll rate, $R_r$ (set at 40°/sec) to the goal bank using:

$$\phi_i = \phi_{i-1} + R_r \cdot dt$$

Once $\phi$ reached $\phi_{goal}$, rolling stopped. When approaching the goal heading, $D_{goal}$, the simulation started rolling out the airplane to 0° bank. The amount of turn still required to reach $D_{goal}$ was calculated:

$$D_{req} = D_{goal} - D$$

The time it took to roll out was calculated:

$$t_{to\_level} = \frac{\phi}{R_r}$$

The estimated amount of heading change the airplane required to execute the roll out was computed using:

$$D_{est} = t_{to\_level} w$$

If $D_{est} > D_{req}$, the simulation started rolling out the airplane. The roll out was gradual, computing a new $\phi_{goal}$ at each time interval (gradually decreasing $\phi_{goal}$ to 0). This was done in 2 steps. First, by computing a desired turn rate:

$$w_{des} = \frac{D_{req}}{t_{to\_level}}$$

Finally, by computing the bank required to accomplish this turn rate:

$$\phi_{des} = \arccos\left(\sqrt{\frac{1}{1+\frac{w_{des}{}^2 V^2}{9.8^2}}}\right)$$

Since the simulation ran in discrete time intervals, both bank angle and heading were artificially limited to the desired bank/heading. This prevented small "overshoots" of the desired values caused by the non-continuous nature of the simulation.

## Intercept Algorithm

The intercept algorithm, or rendezvous procedure, was responsible for providing the goal g and goal heading commands to the simulation engine. The algorithm assumed absolute knowledge of both the UAV and tanker position, altitude, heading and velocity. Simulating a maximum sensor range was accomplished by limiting UAV maneuvering to a pre-designated range from the tanker. Prior to that range, the algorithm commanded straight and level flight. Sensor field-of-regard (azimuth, elevation, and line-of-sight) were used by the algorithm to determine g and heading commands, as well as during post-simulation analysis to assess if the tanker remained inside sensor field-of-regard throughout the rendezvous. The algorithm continuously computed the following parameters (reference Figures 5 and 6):

1. Bear2: Bearing from UAV-to-tanker, and Bear1: vice versa (relative to true north).
2. $LOS2_h$ : "Horizontal line-of-sight" from UAV-to-tanker, and $LOS1_h$ : vice versa (the projection of the line-of-sight to the horizontal plane).
3. The horizontal range between the tanker and UAV ($R_h$).
4. The Cross-track (CT) and Along track (AT) horizontal ranges between the tanker and the UAV, relative to the tanker's current heading.
5. The sensor azimuth and elevation angles (UAV-to-tanker) in body-fixed coordinates system.

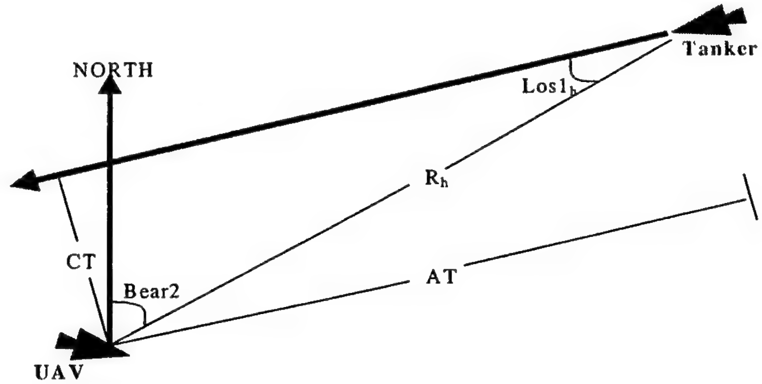


Figure 11. Rendezvous Geometry, God's Eye View

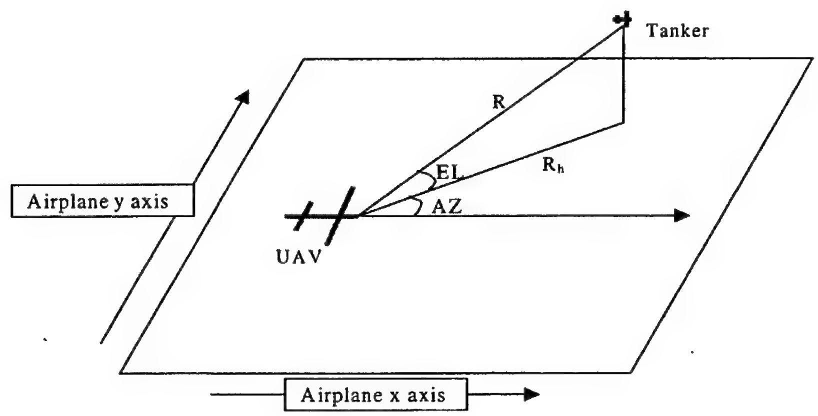


Figure 12. Azimuth and Elevation Definition

Other values computed by the algorithm will be addressed later.

The following assumptions were made:

1. Angle of attack was 0.
2. Angle of sideslip was 0.
3. Sensor bore-sight was on UAV's flight path.
4. Airspeed was held constant throughout every maneuver.
5. Airplane maneuvered in level flight (constant altitude).
6. Maximum g was 2.5 (maximum sustained g).

The algorithm was event driven with one of the events (listed below) in progress at any time. Each event had its own airplane control logic that produced g and heading commands, along with unique logic to decide when to change to a different event. Sample intercepts presented in Figures 7 and 8 to depict each of the seven different events summarized below:

0. "SLUF" - straight and level flight
1. "OPEN" – turned away from the tanker until sensor line-of-sight reached sensor FOR limits, and kept tanker at the maximum sensor line-of-sight thereafter
2. "PARALLEL" – turned toward and flew tanker's reciprocal heading
3. "CLOSE" – turned toward tanker until reaching same heading as tanker
4. "3-POINT" – turned to predicted heading to rendezvous 1 nm in trail of the tanker
5. "PURE PERSUIT" – continuously turned to tanker bearing.
6. "REDUCE CT" – turned to place maximum sensor line-of-sight ahead of tanker (done only if initial cross-track distance was greater than required)

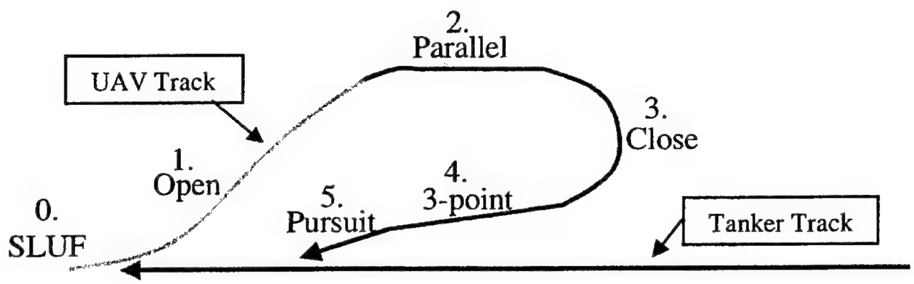


Figure 13. Intercept Scenario with Opening Phase

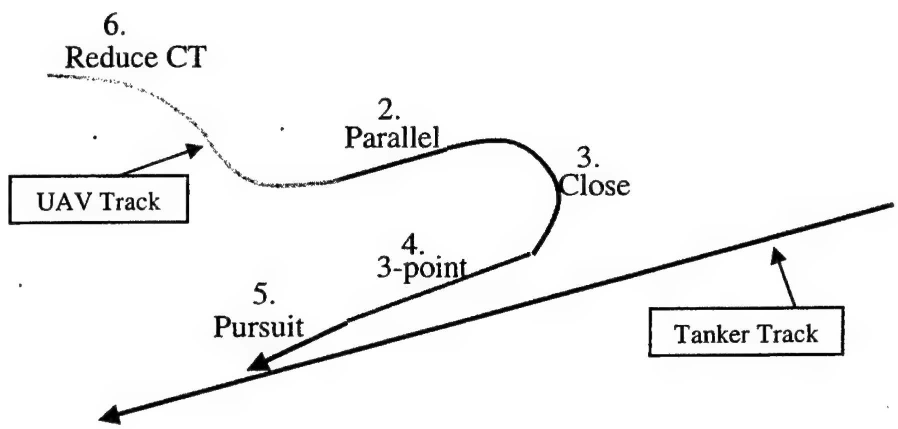


Figure 14. Intercept Scenario with Cross-track Reduction

At each time interval, the algorithm predicted the AT and CT values that would be reached if a closing maneuver was initiated and continued until heading matched tanker's heading. This was done by first calculating the amount of turn required to reach the tanker's heading:

$$\Delta D = D_{tgt} - D_{\text{int}}$$

Then, by calculating the turn rate and bank angle produced by a max g turn (2.5g),

$$w_{\max} = \frac{9.8\sqrt{g_{\max}^{2} - 1}}{V}$$

$$\phi_{\max} = \arccos\left(\frac{1}{g_{\max}}\right)$$

and finally, by calculating the turn radius:

$$r = \frac{V}{w_{\max}}$$

The cross-track and along track distances, as well as the time flown by the UAV during the entire closing maneuver were calculated from:

$$CT_{close} = r(\cos(\Delta D) - 1)$$

$$AT_{close} = r\sin(\Delta D)$$

$$\Delta t = \frac{\Delta D}{w_{\max}}$$

These values assumed an instantaneous g buildup and level off. Since this was not the case as roll rate was set at 40°/sec, $AT_{close}$ was adjusted by adding an estimated along track distance ($AT_{est}$) correction to the tanker and UAV aircraft distances during roll in and roll out of turns:

$$AT_{est} = \frac{\phi + \phi_{\max}}{R_r}\left(V_{tgt} + V\cos(\Delta D - 180)\right)$$

To compute the along track after the closing phase, the distance flown by the tanker during the entire maneuver was added, and the resulting estimate for the along track distance after the closing maneuver was:

$$AT_{after\_close} = AT_{close} - V_{tgt}\Delta t - AT_{est}$$

In a similar manner, the estimated cross-track after the closing maneuver was calculated assuming instantaneous g buildup:

$$CT_{after\_close} = CT - CT_{close}$$

The value of along track and cross-track were calculated for the period from when parallel flying (event 2) was commanded to when the airplane reached reverse parallel heading. For this case, the angle difference and cross-track flown were:

$$\Delta D_{parallel} = D_{tgt} + 180 - D_{\text{int}}$$
$$CT_{parallel} = r\left(\cos\left(\Delta D_{parallel}\right) - 1\right)$$

The estimated cross-track when reaching reverse parallel heading was:

$$CT_{when\_parallel} = CT - CT_{parallel};$$

Another value computed was an estimate of the heading change the UAV flew to reach exactly one nm behind the tanker. This collision course with a point 1 nm behind the tanker was the heading flown during event 4. To calculate this heading difference, the time to reach that point was first computed:

$$t_{3\_po\text{int}} = \frac{\sqrt{AT^2 \cdot V_2^{\,2} + AT \cdot V_2^{\,2} + CT^2\left(V_2^{\,2} - V_1^{\,2}\right) + V_2^{\,2}} - V_1\left(AT - 1\right)}{V_2^{\,2} - V_1^{\,2}}$$

Then, the heading difference was found:

$$\Delta D_{3\_po\text{int}} = \arcsin\left(\frac{CT}{V_2 \cdot t_{3\_po\text{int}}}\right)$$

While allowing the line-of-sight to reach the total sensor limit, the algorithm tried to maintain line-of-sight margin to avoid exceeding the limit. The tolerance, $LOS_{tol}$, for how close to the line-of-sight limit ($LOS_{max}$) was allowed during a maneuver was set (7°) making the maximum commanded line-of-sight:

$$LOS_{\max\_allowed} = LOS_{\max} - LOS_{tol}$$

This limit became even more restrictive as line-of-sight rate increased. This rate of change was computed to remove own ship maneuvering:

$$LOS_{rate\_of\_change} = \frac{LOS_i - LOS_{i-1} + D_i - D_{i-1}}{\Delta t}$$

If this rate was greater than ½ the maximum turn rate, or :

$$LOS_{rate\_of\_change} > \tfrac{1}{2} w_{\max}$$

then the maximum line-of-sight allowed was set at:

$$LOS_{\max\_allowed} = \max\left\{\tfrac{1}{2} LOS_{\max}, LOS_{\max} - 2LOS_{tol}\right\}$$

**Detailed event description**

The following descriptions summarize the individual events of the rendezvous procedure.

Event 0 – SLUF

Event 0 was always the initial event running when the algorithm started. The commands given were:

$$g_{goal} = 1 \qquad ; \qquad D_{goal} = D$$

Change to event 1 (OPEN) occurred if,

$$R_h < Max\_Sensor\_Range \quad \text{AND} \quad 2CT_{close} > CT$$

Or to event 6 (reduce CT) if,

$$R_h < Max\_Sensor\_Range \quad \text{AND} \quad 2CT_{close} < CT$$

Event 1 – OPEN

Open was usually the first event that ran following tanker detection. The UAV was commanded to maneuver to increase the existing cross-track as much as possible while keeping the tanker inside sensor FOR (except for the opening phase where the tanker had negative elevation). The commands given were:

$$g_{goal} = g_{\max} \qquad ; \qquad D_{goal} = Bear_2 + LOS_{\max\_allowed}$$

Change to event 2 (PARALLEL) occurred if,

$$2CT_{close} < CT$$

And to event 3 (CLOSE) if,

$$AT_{after\_close} > 1.3 \text{ Nautical miles}$$

If this created an unsuccessful rendezvous, then CLOSE was delayed by one second increments until a successful rendezvous could be accomplished.

Event 2 – PARALLEL

While this event was running, the algorithm commanded the UAV to fly the tanker's reciprocal heading. If this heading was outside the maximum sensor FOR, the heading for maximum sensor FOR was commanded:

$$g_{goal} = g_{\max} \quad ; \qquad D_{goal} = D_{tgt} + 180$$

Or,

$$g_{goal} = g_{\max} \quad ; \qquad D_{goal} = Bear_2 + LOS_{\max\_allowed}$$

Change to event 3 (CLOSE) occurred if:

$$AT_{after\_close} > 1.3 \text{ Nautical miles}$$

If this created an unsuccessful rendezvous, then CLOSE was delayed by one second increments until a successful rendezvous could be accomplished.

Event 3 - CLOSE

The UAV was commanded to turn toward the tanker's heading. If the UAV was on the right side of the tanker, the turn was a right turn, and opposite for the UAV on the left side.

$$g_{goal} = g_{\max} \quad ; \qquad D_{goal} = D_{tgt}$$

When reaching within 60° of tanker's heading, a change to event 4 was commanded.

Event 4 – 3 POINT

The UAV was commanded to fly to a heading that would bring it to intercept the tanker's flight path at a point 1 NM in trail.

$$g_{goal} = g_{\max} \quad ; \qquad D_{goal} = D_{tgt} - \Delta D_{3\_point}$$

If this heading exceeded the maximum, off bore sight angle limit, the goal heading was limited to the heading resulting in $LOS_{max\_allowed}$ (as before).

A change to event 5 (PURE PURSUIT) occurred when the horizontal range decreased below 0.5 NM.

Event 5 – PURE PURSUIT

The UAV was commanded to fly directly toward the tanker. This event rarely occurred, as the intercept generally reached the desired end game before this distance.

$$g_{goal} = g_{\max} \quad ; \qquad D_{goal} = Bear_2$$

There was no change from this event.

Event 6 – REDUCE CT

During this event, the UAV was commanded to maneuver to decrease the cross-track as much as possible while keeping the tanker inside sensor FOR (opposite of event 1 - "OPEN"). A tolerance – $FOR_{tol}$ – of how close to the FOR limit the maneuver could come was set to 10°, making the maximum allowed line-of-sight:

$$LOS_{2\_\max} = FOR_{\max} - FOR_{tol}$$

The commands given were:

$$g_{goal} = g_{\max} \quad ; \qquad D_{goal} = Bear_2 - LOS_{\max\_allowed}$$

Change to event 3 (CLOSE) occurred if,

$$AT_{after\_close} > 1.3 \text{ Nautical miles}$$

If this created an unsuccessful rendezvous, then CLOSE was delayed by one second increments until a successful rendezvous could be accomplished.

Or a change to event 2 (PARALLEL) if,

$$CT_{when\_parallel} < 3r \qquad \text{(r is the } g_{\max} \text{ turn radius)}$$

**Simulation Iteration**

The MATLAB® simulation was run iteratively to determine the minimum required detection range that allowed successful rendezvous. Two iterative loops were used to accomplish this determination. The first, outer, loop was based on the range at which the UAV starting opening, the initial range. This loop started at 20 nm and used a halving technique to search for the minimum initial range that resulted in successful rendezvous. The second, inner, loop varied the point in the rendezvous where the UAV would begin closing. For each of the initial ranges, the second loop would vary the point during the rendezvous where the UAV could close and arrive at a successful end game. The close point was varied using time delay in increments of 1 second. For each of the different

closing points, minimum horizontal range to the tanker and maximum UAV-to-tanker line-of-sight, azimuth and elevation were evaluated against the rendezvous success criteria. In cases where multiple close points resulted in a successful rendezvous, the rendezvous that ended closer to the tanker or required less time to complete were chosen as the best procedure. The result of these two, iterative loops was a determination of the minimum range for each sensor configuration and aspect angle simulated, along with the procedure commands and timing for the successful rendezvous.

# APPENDIX C: MATLAB® SIMULATION RESULTS

Table 2. Minimum Sensor Range for Successful Rendezvous (NM)

| Aspect | Sensor Field-of-regard (FOR) – Azimuth / Elevation ± 90° AFRL Potential Radar Sensor | ± 80° | ± 70° | ± 60° | ± 50° | ± 40° | ± 30° | ± 40° / ± 70° AFRL Potential EO Sensor |
|---|---|---|---|---|---|---|---|---|
| 180° | 6.3 | 6.9 | 7.8 | 9.2 | 11.6 | 16.8 | > 20 | 12.0 |
| 175° | 5.7 | 6.3 | 6.9 | 7.9 | 9.6 | 13.0 | > 20 | 9.3 |
| 170° | 5.2 | 5.7 | 6.3 | 7.0 | 8.1 | 10.4 | 15.4 | 7.5 |
| 165° | 4.6 | 5.2 | 5.7 | 6.2 | 7.0 | 8.6 | 11.8 | 6.2 |
| 160° | 4.0 | 4.6 | 5.2 | 5.7 | 6.0 | 7.2 | 9.3 | 5.3 |
| 155° | 3.5 | 4.1 | 4.7 | 5.2 | 5.4 | 6.2 | 7.7 | 4:5 |
| 150° | 3.1 | 3.7 | 4.2 | 4.8 | 4.9 | 5.3 | 6.4 | 4.0 |
| 145° | 2.7 | 3.3 | 3.8 | 4.4 | 4.6 | 4.7 | 5.4 | 3.6 |
| 140° | 2.4 | 3.0 | 3.5 | 4.1 | 4.2 | 4.3 | 4.7 | 3.1 |
| 130° | 1.9 | 2.4 | 2.8 | 3.5 | 3.6 | 3.5 | 3.7 | 2.6 |
| 120° | 1.5 | 1.9 | 2.4 | 2.8 | 3.2 | 3.1 | 3.0 | 2.2 |
| 110° | 1.3 | 1.6 | 1.9 | 2.3 | 2.7 | 2.7 | 2.6 | 1.8 |
| 100° | 1.1 | 1.3 | 1.6 | 1.9 | 2.2 | 2.4 | 2.3 | 1.5 |
| 090° | 0.9 | 1.1 | 1.3 | 1.5 | 1.7 | 2.0 | 2.0 | 1.3 |
| | Tanker Maneuver at Start Maneuver (Initial Open) | | | | | | | |
| 180° | 4.8 | 5.2 | 5.6 | 6.0 | 6.4 | 7.3 | 8.4 | 5.9 |
| | Tanker Maneuver into UAV at Closing Maneuver (Initial Close) | | | | | | | |
| 180° | 8.2 | 8.0 | 8.6 | 10.4 | 13.3 | 18.8 | > 20 | 12.9 |
| | Tanker Maneuver away at Closing Maneuver (Initial Close) | | | | | | | |
| 180° | 5.4 | 5.9 | 6.4 | 7.3 | 9.3 | 14.8 | > 20 | 9.3 |

Assumptions utilized in the determination of the minimum sensor range for a successful rendezvous.

1. Maneuver algorithm used is the test-team provided algorithm
2. Tanker 417 KTAS, UAV 445 KTAS
3. Tanker 1000 feet higher than UAV
4. Tanker non-maneuvering
5. UAV maneuvers at 2.5 g's sustained turn
6. UAV roll rate is 40 deg/sec
7. Instantaneous UAV autopilot response to algorithm command
8. UAV sensor instantaneous lock at this range
9. UAV sensor outputs tanker exact position and velocity vector
10. Constant and same wind for UAV and tanker
11. Continuous sensor lock

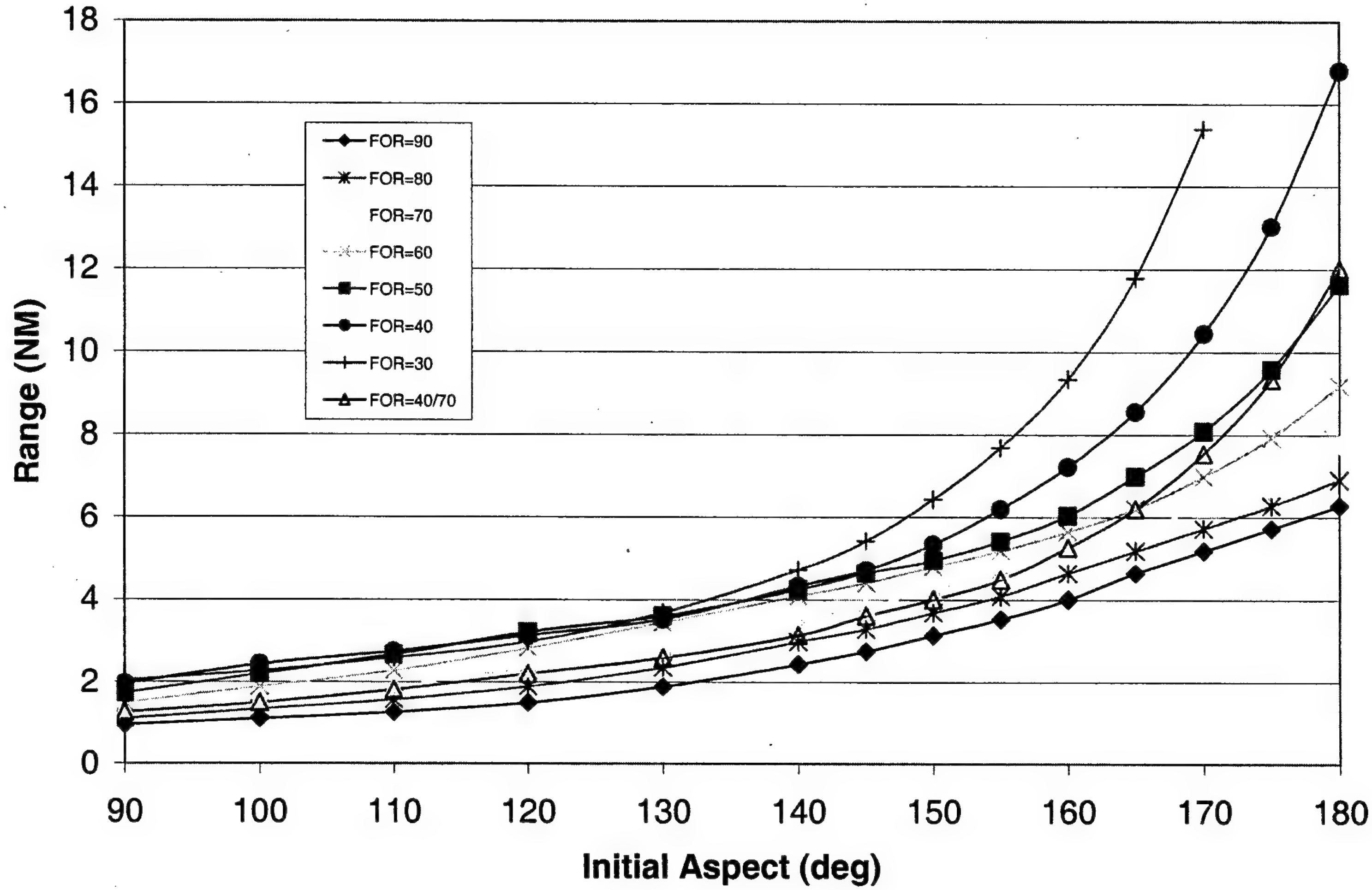


Figure 15. Minimum Sensor Range Results

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# APPENDIX D: D-6 SIMULATION TEST CASES

Table 3. D-6 Simulation Cases

| Test Point | Field-of-regard | Test Condition |
|---|---|---|
| 1 | 90° | Aspect: 180<br>Action: Min + 15% |
| 2 | 90° | Aspect: 180<br>Action: Min |
| 3 | 90° | Aspect: 180<br>Action: Min - 15% |
| 4 | 90° | Aspect: 170<br>Action: Min + 15% |
| 5 | 90° | Aspect: 160<br>Action: Min + 15% |
| 6 | 90° | Aspect: 150<br>Action: Min + 15% |
| 7 | 90° | Aspect: 150<br>Action: Min |
| 8 | 90° | Aspect: 150<br>Action: Min - 15% |
| 9 | 90° | Aspect: 140<br>Action: Min + 15% |
| 10 | 90° | Aspect: 180<br>Action: Min + 15%<br>Tanker 20° Bank<br>Turn Away at<br>Opening Maneuver |
| 11 | 90° | Aspect: 180<br>Action: Min + 15%<br>Tanker 20° Bank<br>Turn Away at<br>Closing Maneuver |

| Test Point | Field-of-regard | Test Condition |
|---|---|---|
| 12 | 40° / 70° | Aspect: 180<br>Action: Min + 15% |
| 13 | 40° / 70° | Aspect: 180<br>Action: Min |
| 14 | 40° / 70° | Aspect: 180<br>Action: Min - 15% |
| 15 | 40° / 70° | Aspect: 170<br>Action: Min + 15% |
| 16 | 40° / 70° | Aspect: 160<br>Action: Min + 15% |
| 17 | 40° / 70° | Aspect: 150<br>Action: Min + 15% |
| 18 | 40° / 70° | Aspect: 150<br>Action: Min |
| 19 | 40° / 70° | Aspect: 150<br>Action: Min - 15% |
| 20 | 40° / 70° | Aspect: 140<br>Action: Min + 15% |
| 21 | 40° / 70° | Aspect: 180<br>Action: Min + 15%<br>Tanker 20° Bank<br>Turn Away at<br>Opening Maneuver |
| 22 | 40° / 70° | Aspect: 180<br>Action: Min + 15%<br>Tanker 20° Bank<br>Turn Away at<br>Closing Maneuver |

Table 3 outlines the test point conditions used for runs in D-6. These same points were used to collect data during flight test. Results of the D-6 runs are located in Appendix E, and the results from flight test are found in Appendix F and G. The intercept numbers used to name each maneuver in Appendix F are consistent with the test points above. The configurations in Table 3 reflect customer priorities for flight test.

# APPENDIX E: D-6 SIMULATION RESULTS

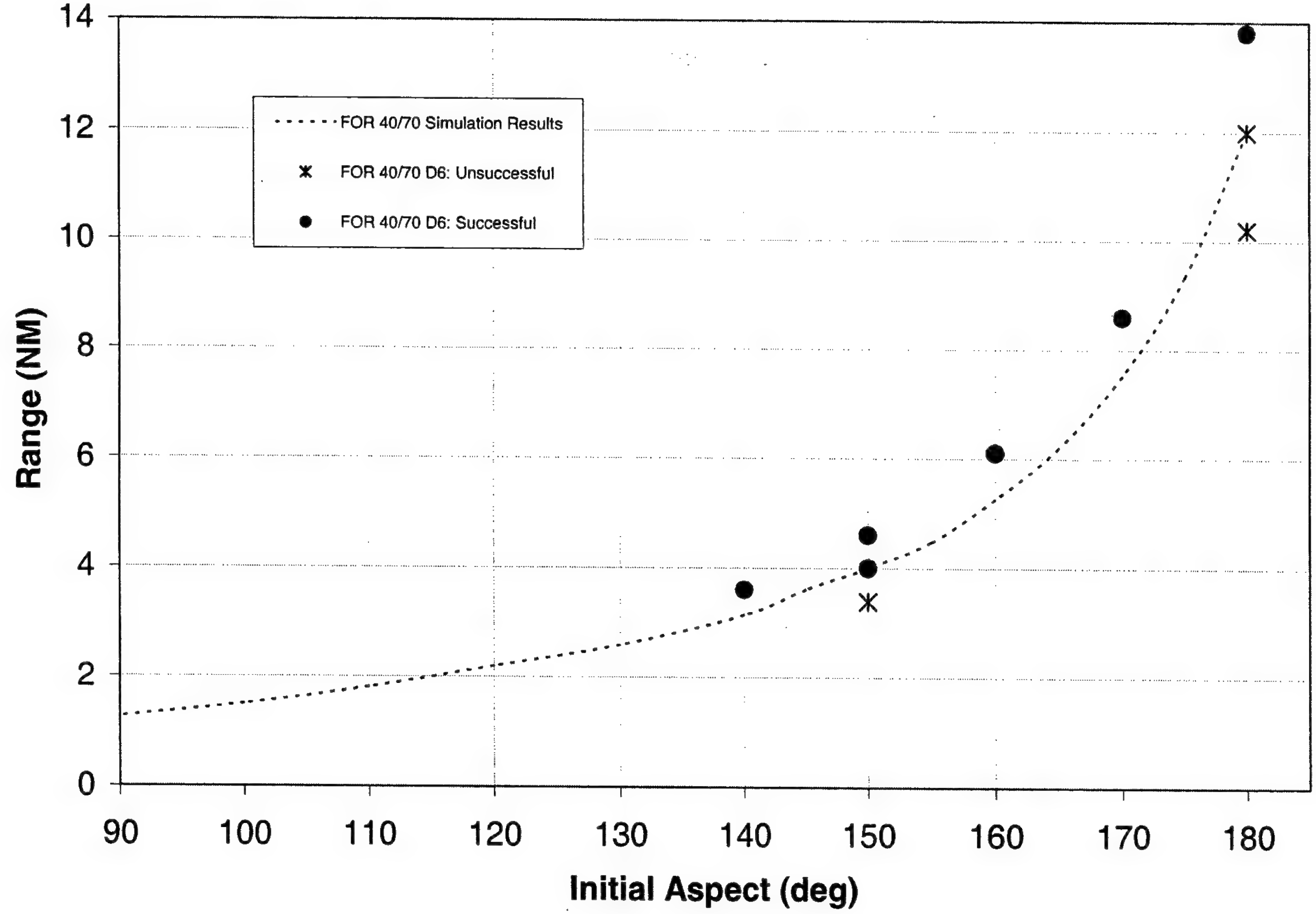


Figure 16. D-6 Simulation Results, 40° by 70° Sensor

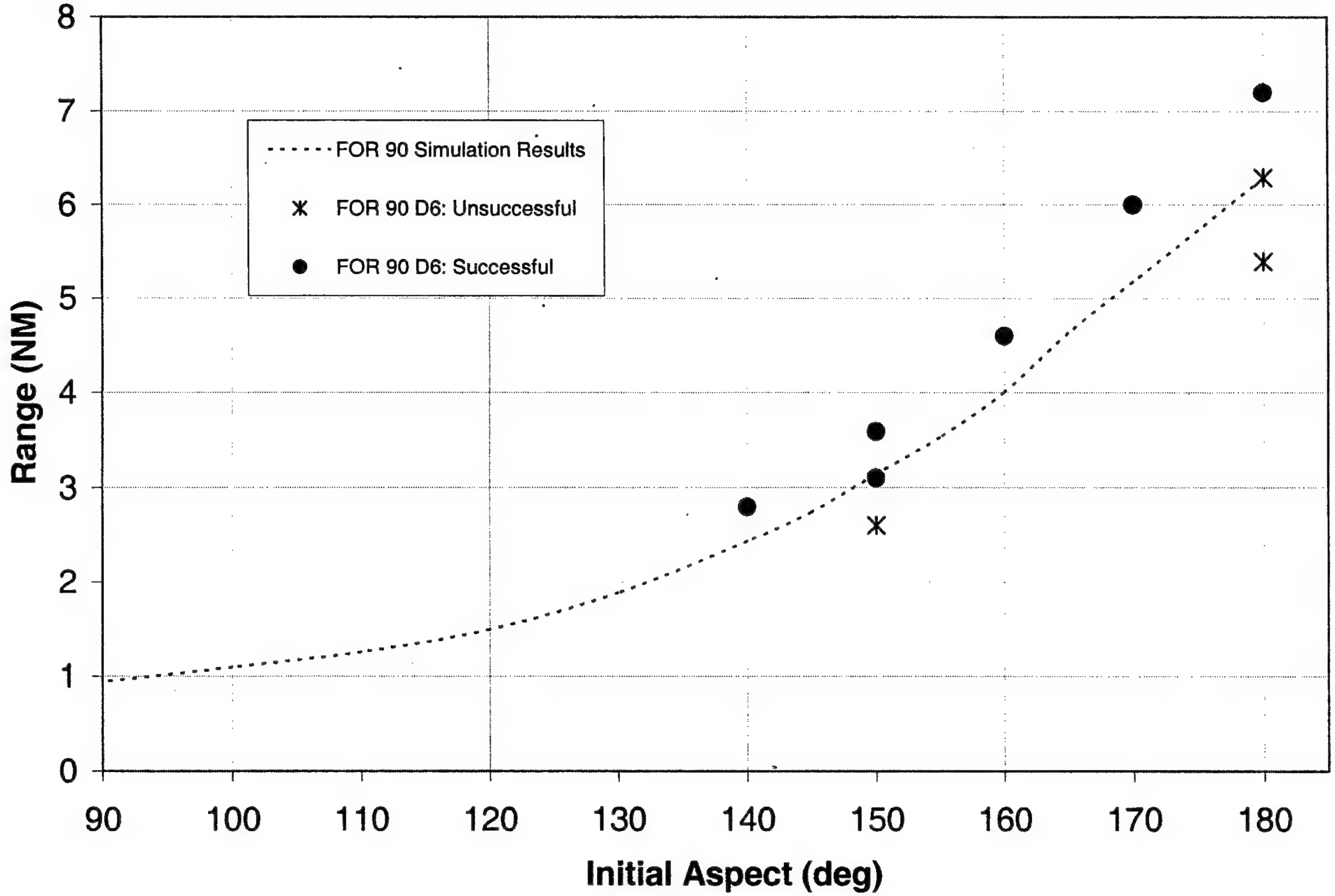


Figure 17. D-6 Simulation Results, 90° Sensor

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# APPENDIX F: FLIGHT TEST RESULTS BY RENDEZVOUS

The following pages present individual comparisons of flight test and MATLAB® simulation results for each of the rendezvous cases that were flight tested. The rendezvous results are ordered by intercept number consistent with the D-6 cases presented in Appendix C. The MATLAB® simulation results were generated using the actual flight test intercept initial conditions and average airspeed for UAV and tanker. Therefore, the differences in results were attributed to slight variations by the test pilot in recreating the rendezvous scenario.

The first rendezvous data page is an example that provides some description of the four section construction. The upper left-hand of the each page shows the planned initial aspect and range of the intercept, along with the UAV (test) and tanker (target) planned and actual true airspeeds during the maneuver. The test sortie (one of three) and the date of the test are also shown. The upper right displays a God's eye view of the intercept tracks. The matching shades and arrows of the UAV and tanker tracks time-stamp points on the track to present relative positioning throughout the maneuver. The lower right section of the page shows time histories of key parameters for the rendezvous. The heavy dashed line in the line-of-sight trace represents the max line-of-sight limit. Finally, the lower left section of each page presents a table comparing key flight test and simulation (based on flight test conditions) parameters. The success criteria parameter indicates "yes" if the rendezvous passes all four rendezvous success criteria, and indicates "no" if the rendezvous fails any of the four. The remaining parameters are self-explanatory.

A major factor in determining the data quality of the rendezvous was whether or not the flight test tolerances were maintained. Although the pilot execution in recreating the rendezvous was of little interest to the customer, the magnitude of the tolerances should be of concern because those tolerances established some form of bound on the level of tracking error an autopilot would be allowed during the rendezvous. Listed below are the tolerances used during flight test with the expected error or error propagation rate shown in parentheses.

1. Maneuver initiation lead/lag – desired g achieved within 0.2NM of desired distance (0.2 NM error induced).
2. Heading difference - ±5° during non-maneuvering portions of the intercept (0.01NM/sec).
3. Airspeed changes – average airspeed difference of ±10 KTAS and instantaneous difference of ±30 KTAS (0.003 NM/sec)
4. g – g capture will be to within ±0.2g of desired g (0.015 NM/sec)
5. Wind – total wind change of less than ±10 knots from average wind (at both UAV and tanker altitudes) will be considered "in tolerance". Greater wind changes will require the simulated intercept to corrected with the wind components at each specific time in the intercept (0.003 NM/sec).

The propagated position error for the test aircraft expected by these errors (root sum squared), assuming two maneuver initiations ("OPEN" and "CLOSE") in nautical miles was propagated through the intercept in the following manner.

Initially, Error was set to 0.2NM:

$$Error_{t0} = 0.2$$

For maneuvering portions of the intercept, the error was:

$$Error_{t2} = Error_{t1} + 0.016(t2 - t1)$$

While for non-maneuvering parts, the error was:

$$Error_{t2} = Error_{t1} + 0.011(t2 - t1)$$

For the tanker (assuming no maneuvering), the error was:

$$Error = 0.01t$$

If the entire maneuver position difference, as a function of time, between the flight test data and the simulation was bounded by these errors, the maneuver was considered a successful recreation of the simulation rendezvous.

Using this methodology, when the flight tolerances were maintained, the simulation and flight test rendezvous matched well with the simulation successfully predicting flight test rendezvous outcomes.

**EXAMPLE** **EXAMPLE** **EXAMPLE**

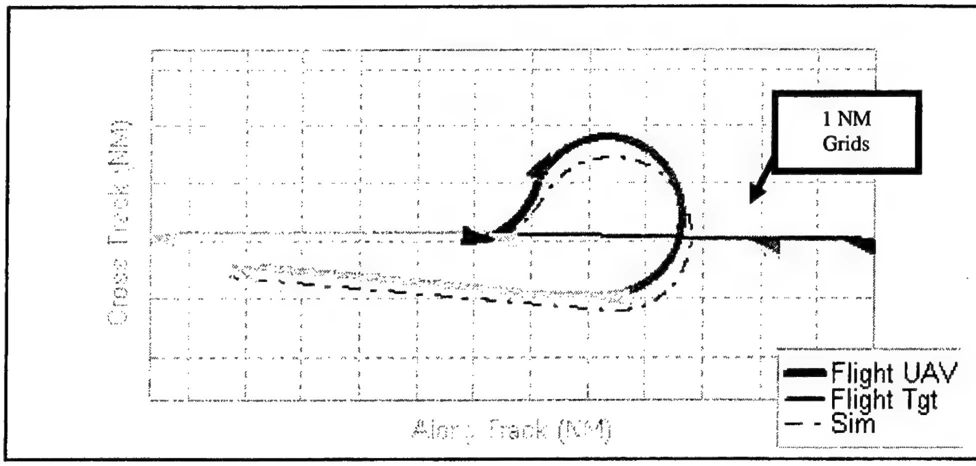
# Intercept ##

## Open Range ($R_{min-15\%}$, $R_{min}$, $R_{min+15\%}$)

Flight #: Date

### Planned Intercept Parameters

Sensor Capability: Az° / El°
Initial Aspect: 180
Range at Open (NM): 7.2
UAV
Altitude (ft MSL): 27000
Planned Speed (TAS): 445
*Actual Avg Speed (TAS): 453*
Tanker
Altitude (ft MSL): 28000
Planned Speed (TAS): 417
*Actual Avg Speed (TAS): 417*

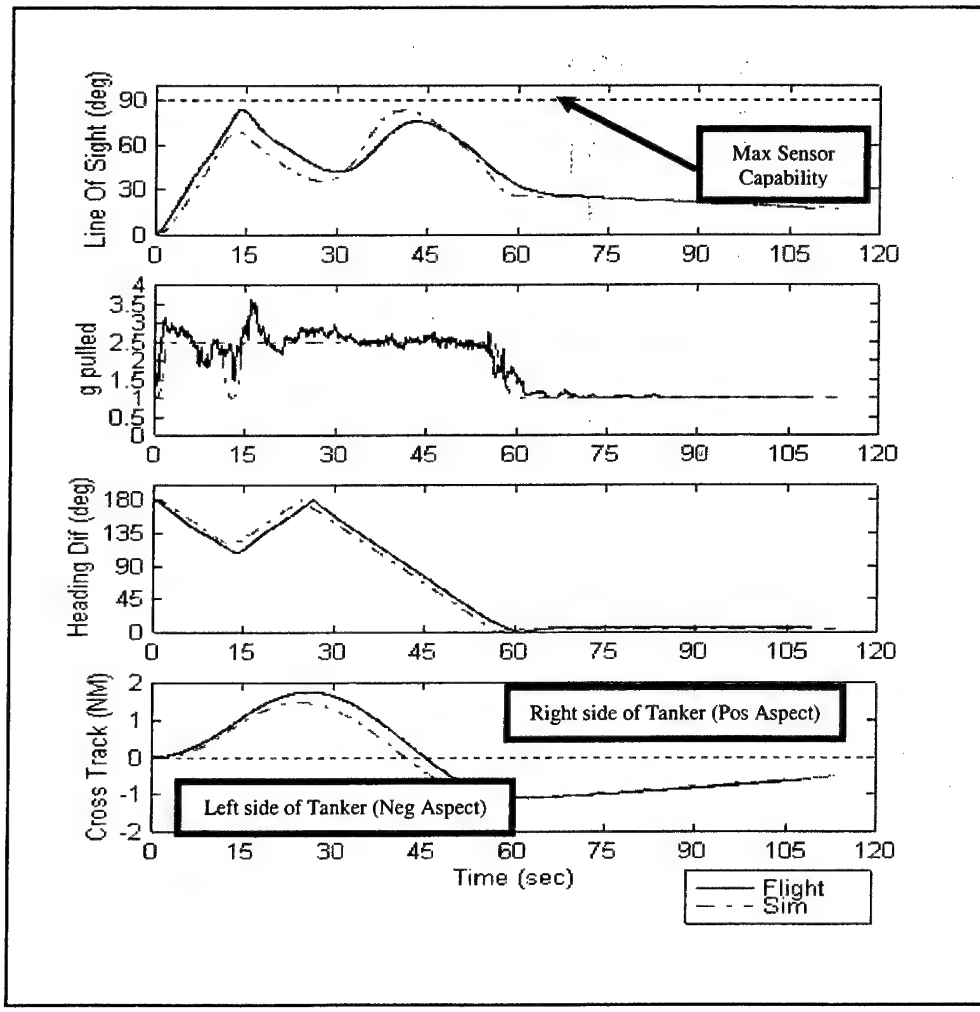



### Simulation/Flight Comparison

| Parameter *(Note 1)* | Sim | Flight |
|---|---|---|
| Initial Aspect (deg) *(Note 2)* | -180.0 | 179.9 |
| Horz Range (NM) | 7.2 | 7.2 |
| Success Criteria? | Yes | Yes |
| Max Cross-track (NM) | 1.5 | 1.8 |
| Max Line-of-Sight (deg) | 83.2 | 83.7 |
| Max Az (deg) | 67.5 | 83.1 |
| Max El (deg) | 80.5 | 81.8 |
| Min Range (NM) | 1.0 | 1.2 |
| End Range (NM) | 1.5 | 1.5 |
| End Aspect (NM) | -20.0 | -23.0 |
| End ΔHead (deg) | 5.2 | 7.0 |
| Time El is < 0 (sec) *(Note 3)* | 11.3 | 13.5 |

***Notes:***

1. *Flight results are those obtained from post flight data. Sim results are based on simulation data re-run from average flight conditions (i.e. heading, speed).*
2. *Negative aspect is left aspect*
3. *Time UAV is belly-up to tanker (No sensor look-down capability).*

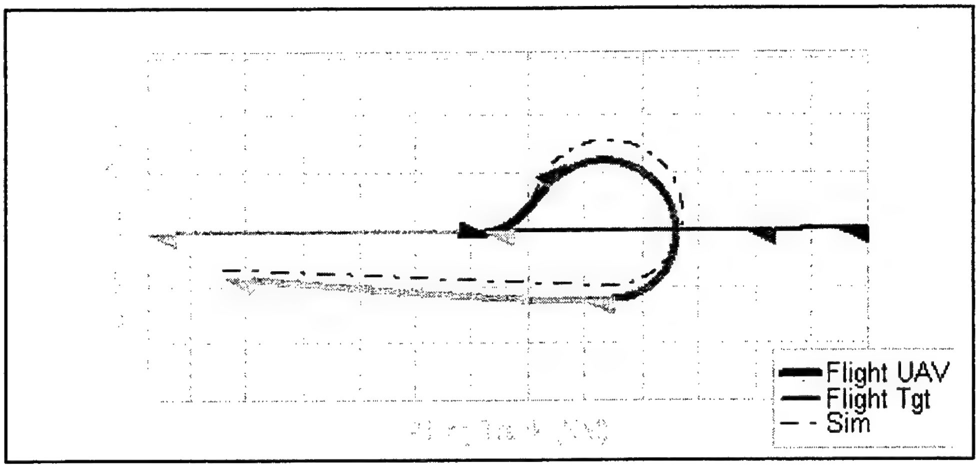



Comments

# Intercept 1 (Flight 1, Attempt 2)

## $R_{min+15\%}$

Flight 1: 8 Oct 2003




### Planned Intercept Parameters

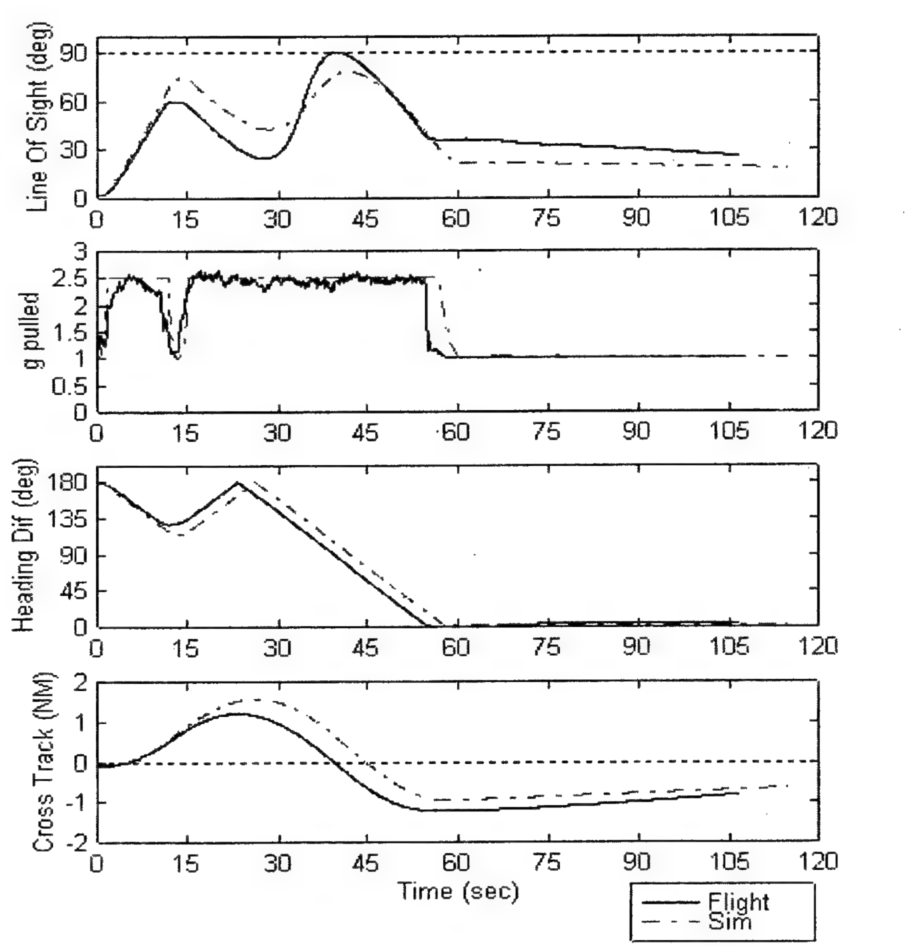
Sensor: 90 / 90 (Az° / El°)
Initial Aspect: 180
Range at Open (NM): 7.2

UAV
- Altitude (ft MSL): 27000
- Planned Speed (TAS): 445
- *Actual Avg Speed (TAS): 446*

Tanker
- Altitude (ft MSL): 28000
- Planned Speed (TAS): 417
- *Actual Avg Speed (TAS): 421*

### Simulation/Flight Comparison

| Parameter | Sim | Flight |
|---|---|---|
| Initial Aspect (deg) | -179.1 | -179.4 |
| Horz Range (NM) | 7.2 | 7.2 |
| Success Criteria? | Yes | No |
| Max CT (NM) | 1.6 | 1.2 |
| Max LOS (deg) | 78.4 | 90.6 |
| Max Az (deg) | 74.1 | 59.3 |
| Max El (deg) | 75.2 | 87.1 |
| Min Range (NM) | 1.2 | 0.7 |
| End Range (NM) | 1.9 | 1.6 |
| End Aspect (NM) | -20.0 | -30.5 |
| End ΔHead (deg) | 2.6 | 5.3 |
| Time El is < 0 (sec) (Sensor Breaklock) | 12.1 | 10.5 |




### Comments

UAV did not fully open to desired heading causing insufficient cross-track and max line-of-sight was exceeded. The 90° sensor was very sensitive to slight variations in cross-track as maneuvering took place at very close ranges. A similar cross-track deviation had a greater magnitude impact on line-of-sight.

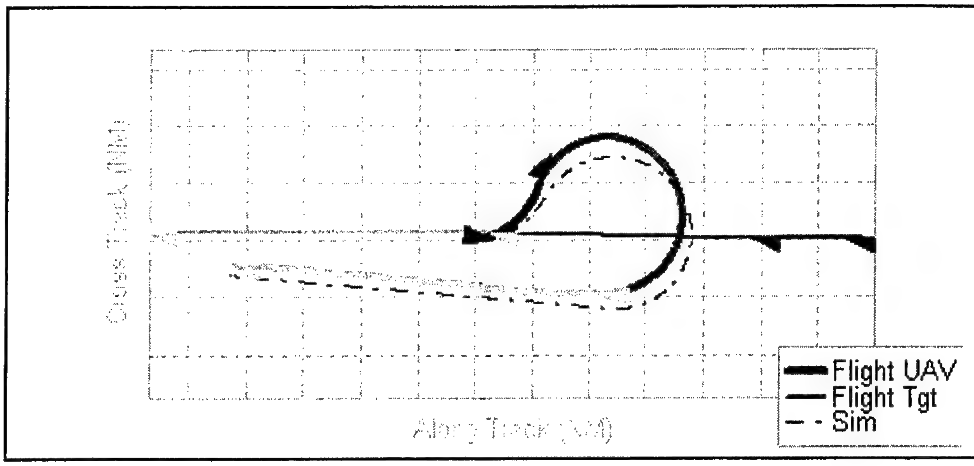
# Intercept 1 (Flight 3, Attempt 2)

## $R_{min+15\%}$

Flight 3: 28 Oct 2003

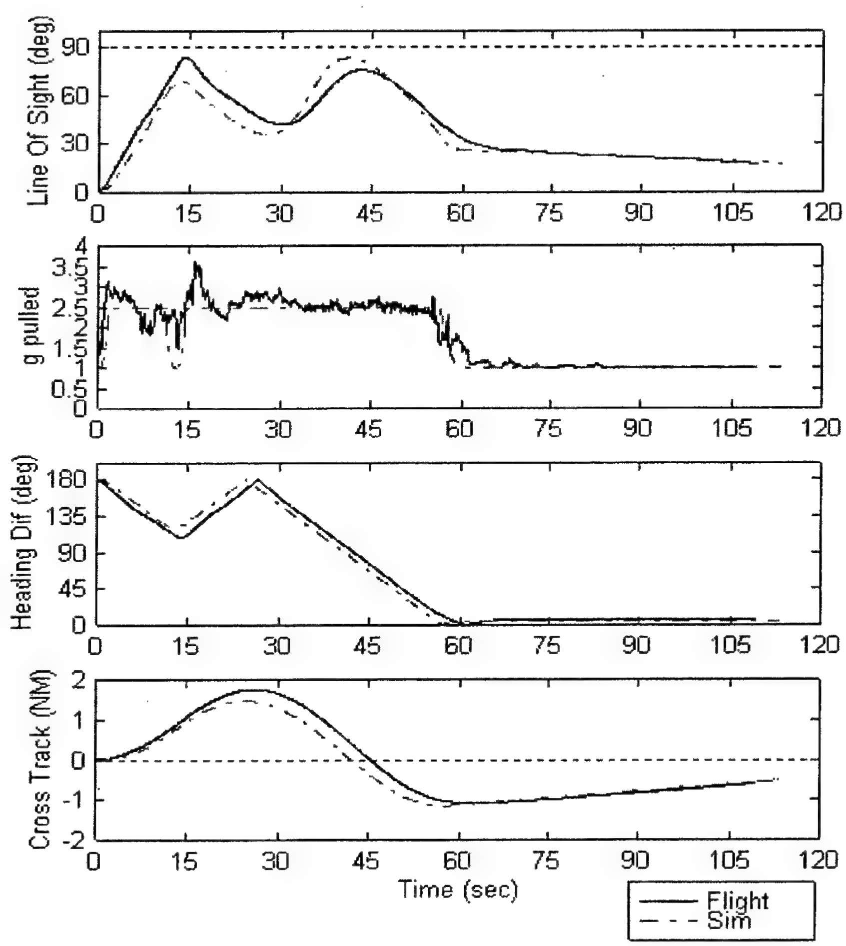
**Planned Intercept Parameters**

Sensor: 90 / 90 (Az° / El°)
Initial Aspect: 180
Range at Open (NM): 7.2
UAV
  Altitude (ft MSL): 27000
  Planned Speed (TAS): 445
  *Actual Avg Speed (TAS): 453*
Tanker
  Altitude (ft MSL): 28000
  Planned Speed (TAS): 417
  *Actual Avg Speed (TAS): 417*




**Simulation/Flight Comparison**

| Parameter | Sim | Flight |
|---|---|---|
| Initial Aspect (deg) | -180.0 | 179.9 |
| Horz Range (NM) | 7.2 | 7.2 |
| Success Criteria? | Yes | Yes |
| Max CT (NM) | 1.5 | 1.8 |
| Max LOS (deg) | 83.2 | 83.7 |
| Max Az (deg) | 67.5 | 83.1 |
| Max El (deg) | 80.5 | 81.8 |
| Min Range (NM) | 1.0 | 1.2 |
| End Range (NM) | 1.5 | 1.5 |
| End Aspect (NM) | -20.0 | -23.0 |
| End ΔHead (deg) | 5.2 | 7.0 |
| Time El is < 0 (sec) (Sensor Breaklock) | 11.3 | 13.5 |

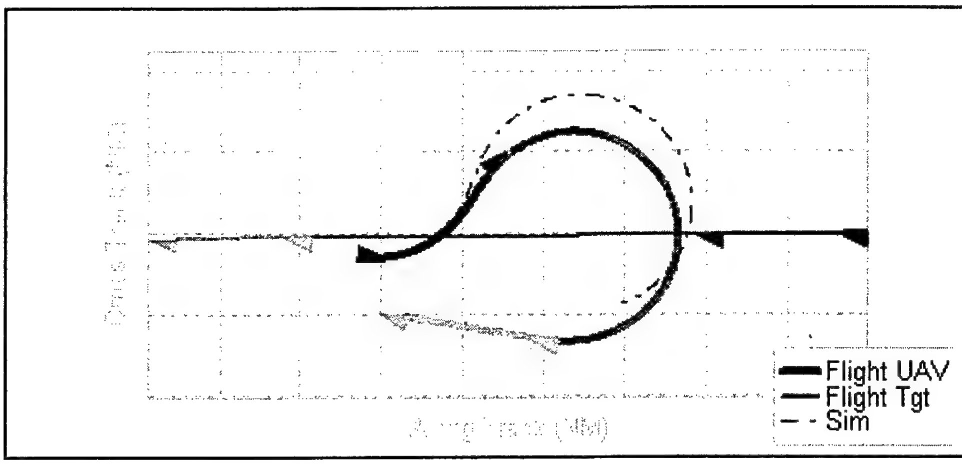



**Comments**

Slightly more open than required but within tolerances.

# Intercept 2
## $R_{min}$

Flight 1: 8 Oct 2003

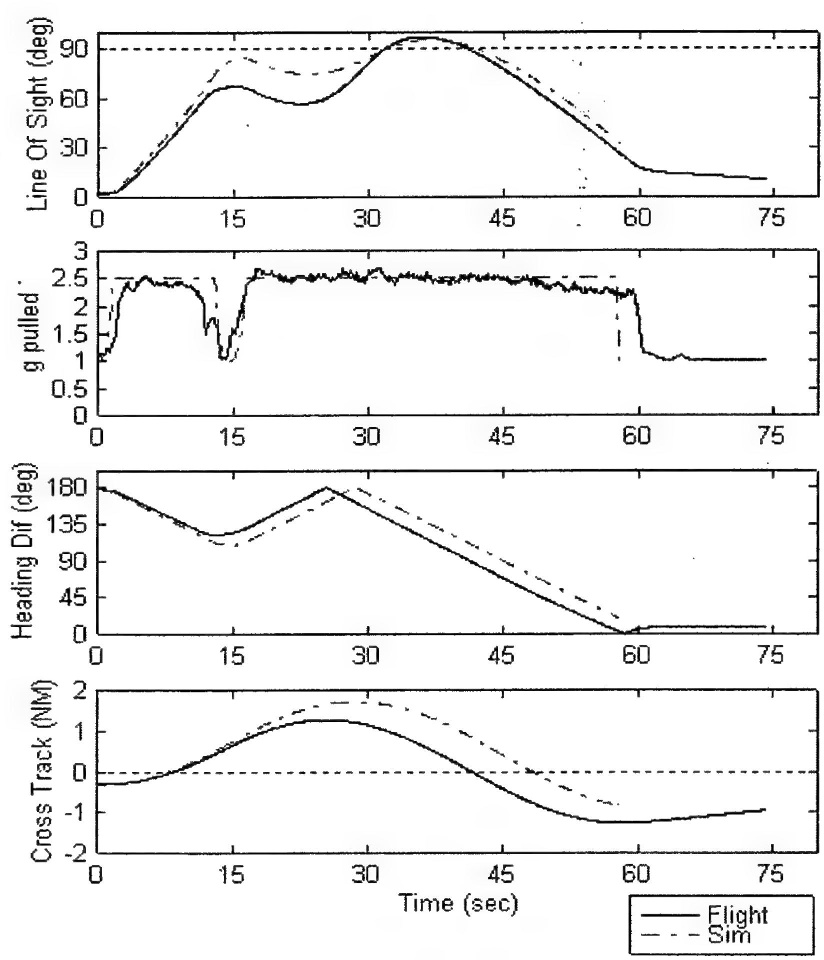



Planned Intercept Parameters

Sensor: 90 / 90 (Az° / El°)
Initial Aspect: 180
Range at Open (NM): 6.3
UAV
Altitude (ft MSL): 27000
Planned Speed (TAS): 445
*Actual Avg Speed (TAS): 454*
Tanker
Altitude (ft MSL): 28000
Planned Speed (TAS): 417
*Actual Avg Speed (TAS): 423*

Simulation/Flight Comparison

| Parameter | Sim | Flight |
|---|---|---|
| Initial Aspect (deg) | -177.1 | -177.3 |
| Horz Range (NM) | 6.3 | 6.3 |
| Success Criteria? | No | No |
| Max CT (NM) | 1.7 | 1.3 |
| Max LOS (deg) | 95.6 | 97.2 |
| Max Az (deg) | 83.0 | 65.0 |
| Max El (deg) | 91.0 | 91.0 |
| Min Range (NM) | 1.7 | 1.2 |
| End Range (NM) | 3.7 | 3.0 |
| End Aspect (NM) | -13.0 | -18.6 |
| End ΔHead (deg) | 19.7 | 9.8 |
| Time El is < 0 (sec) (Sensor Breaklock) | 13.0 | 10.9 |




Comments

The initial aspect of 177 left, causing an adverse cross-track of 0.3 NM at the open maneuver, caused the rejoin to be outside of tolerances. Referencing the cross-track chart on the right, if the initial maneuver would have been to the right, to remain on the left side of the tanker, the rejoin would have succeeded. Slight deviations in aspect at $R_{min}$ maneuver resulted in an unsuccessful rejoin.

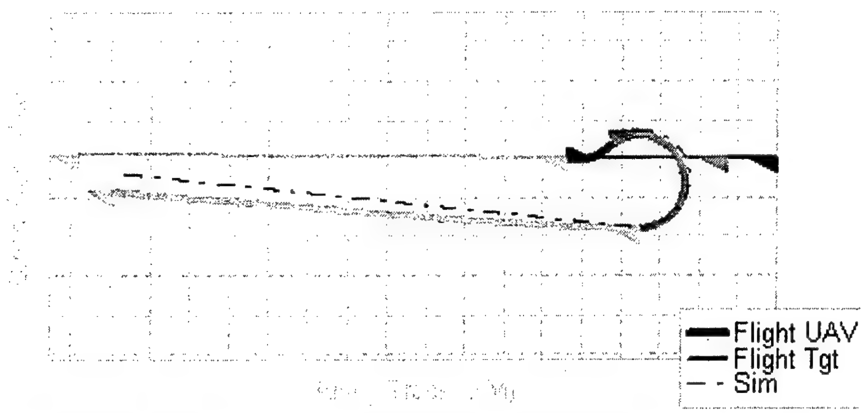
# Intercept 3

## $R_{min-15\%}$

Flight 1: 8 Oct 2003

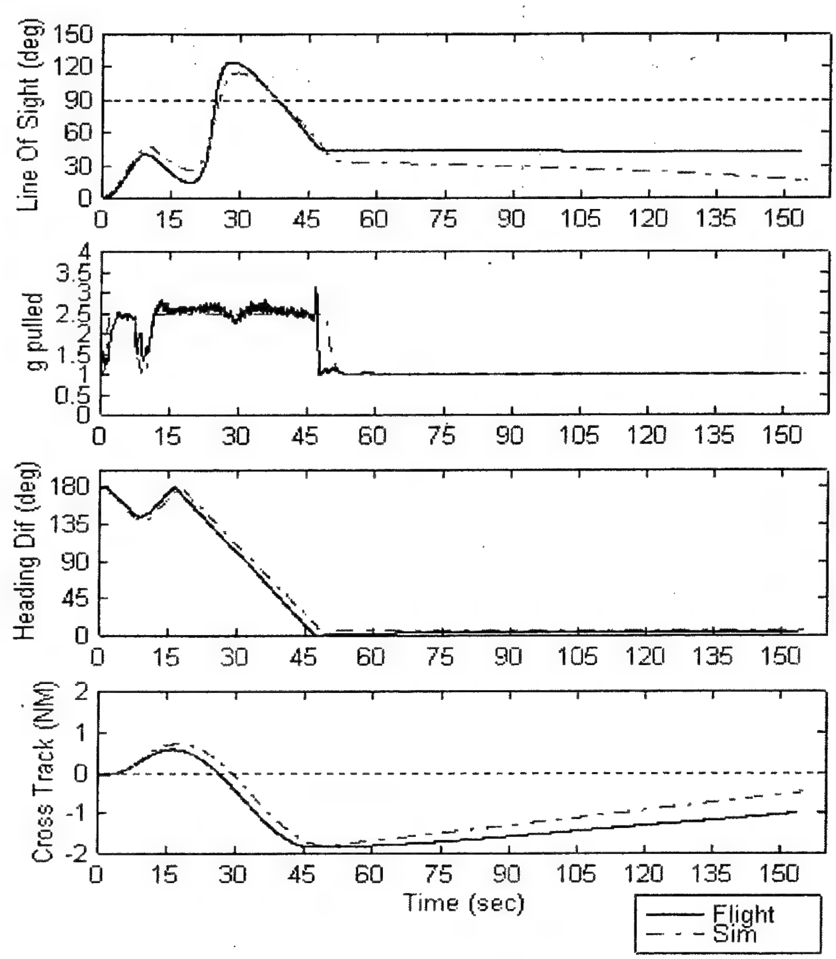
<u>Planned Intercept Parameters</u>

Sensor: 90 / 90 (Az° / El°)
Initial Aspect: 180
Range at Open (NM): 5.4
<u>UAV</u>
Altitude (ft MSL): 27000
Planned Speed (TAS): 445
*Actual Avg Speed (TAS): 444*
<u>Tanker</u>
Altitude (ft MSL): 28000
Planned Airspeed (TAS): 417
*Actual Avg Speed (TAS): 411*




<u>Simulation/Flight Comparison</u>

| Parameter | Sim | Flight |
|---|---|---|
| Initial Aspect (deg) | -179.4 | -179.7 |
| Horz Range (NM) | 5.4 | 5.4 |
| Success Criteria? | No | No |
| Max CT (NM) | 0.7 | 0.6 |
| Max LOS (deg) | 115.0 | 124.5 |
| Max Az (deg) | 45.9 | 55.4 |
| Max El (deg) | 110.4 | 123.3 |
| Min Range (NM) | 0.5 | 0.2 |
| End Range (NM) | 1.4 | 1.4 |
| End Aspect (NM) | -20.0 | -46.4 |
| End ΔHead (deg) | 5.9 | 4.7 |
| Time El is < 0 (sec) (Sensor Breaklock) | 7.8 | 7.3 |

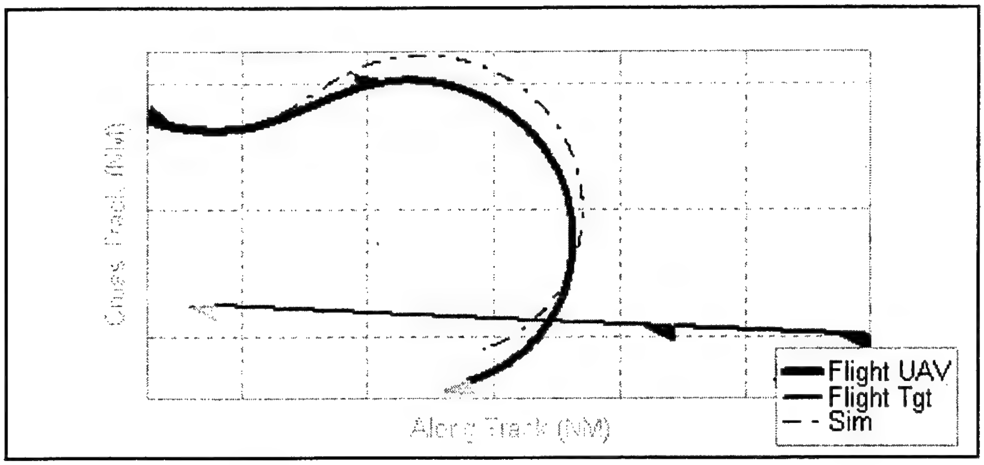



<u>Comments</u>

Very close to simulation until the end of the close. A heading difference of 2° during a long "chase" caused some cross-track deviations at end-game.

# Intercept 4 (Flight 2)
## $R_{min+15\%}$

Flight 2: 17 Oct 2003




### Planned Intercept Parameters

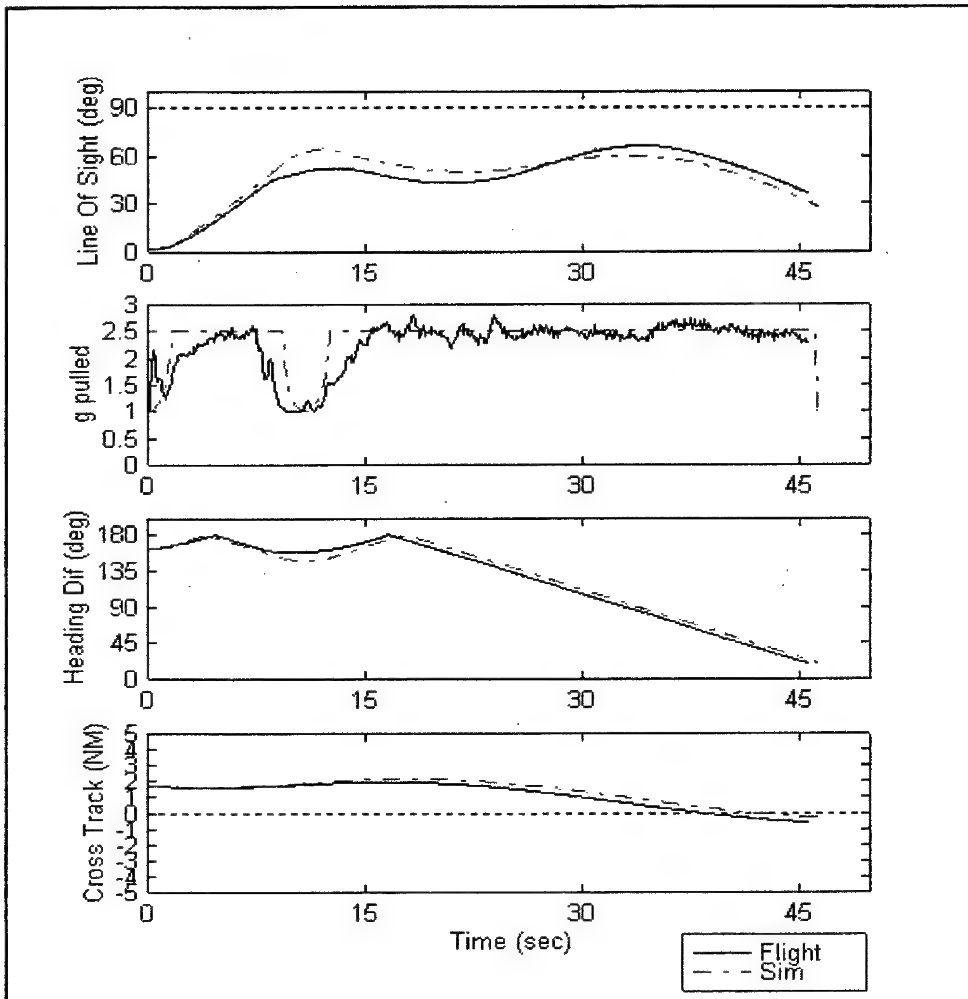
Sensor: 90 / 90 (Az° / El°)
Initial Aspect: 170
Range at Open (NM): 6.0

UAV
- Altitude (ft MSL): 27000
- Planned Speed (TAS): 445
- *Actual Avg Speed (TAS): 446*

Tanker
- Altitude (ft MSL): 28000
- Planned Speed (TAS): 417
- *Actual Avg Speed (TAS): 421*

### Simulation/Flight Comparison

| Parameter | Sim | Flight |
|---|---|---|
| Initial Aspect (deg) | 163.4 | 163.6 |
| Horz Range (NM) | 6.0 | 6.0 |
| Success Criteria? | Yes | Yes |
| Max CT (NM) | 2.2 | 1.9 |
| Max LOS (deg) | 64.7 | 66.3 |
| Max Az (deg) | 62.7 | 49.7 |
| Max El (deg) | 60.1 | 62.2 |
| Min Range (NM) | 1.7 | 1.4 |
| End Range (NM) | 2.2 | 2.1 |
| End Aspect (NM) | -7.9 | -16.6 |
| End ΔHead (deg) | 19.8 | 19.7 |
| Time El is < 0 (sec) (Sensor Breaklock) | 9.6 | 8.1 |



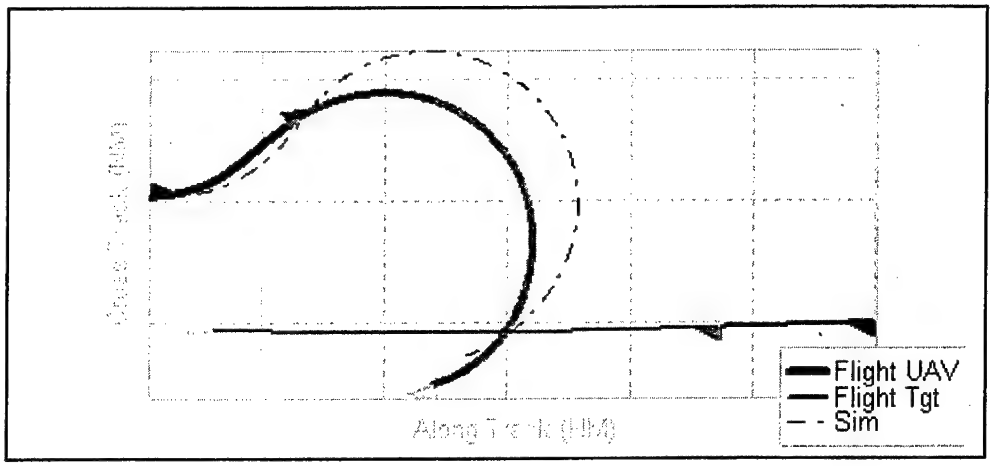

### Comments

None.

# Intercept 4 (Flight 3)

## $R_{min+15\%}$

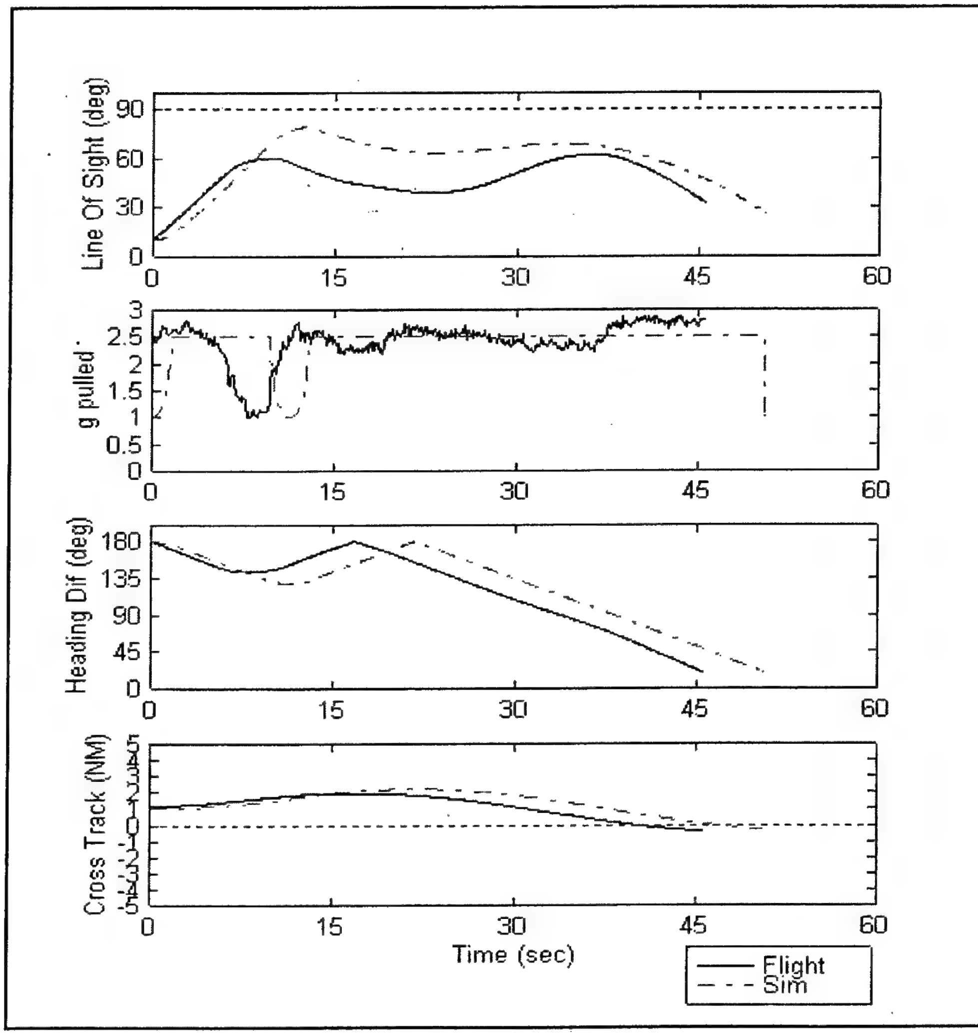
Flight 3: 28 Oct 2003




### Planned Intercept Parameters

Sensor: 90 / 90 (Az° / El°)
Initial Aspect: 170
Range at Open (NM): 6.0
UAV
- Altitude (ft MSL): 27000
- Planned Speed (TAS): 445
- *Actual Avg Speed (TAS): 450*

Tanker
- Altitude (ft MSL): 28000
- Planned Speed (TAS): 417
- *Actual Avg Speed (TAS): 412*




### Simulation/Flight Comparison

| Parameter | Sim | Flight |
|---|---|---|
| Initial Aspect (deg) | 170.0 | 168.9 |
| Horz Range (NM) | 6.0 | 6.0 |
| Success Criteria? | Yes | Yes |
| Max CT (NM) | 2.2 | 2.0 |
| Max LOS (deg) | 79.1 | 62.3 |
| Max Az (deg) | 77.0 | 57.7 |
| Max El (deg) | 73.4 | 58.7 |
| Min Range (NM) | 2.0 | 1.3 |
| End Range (NM) | 2.7 | 1.8 |
| End Aspect (NM) | -6.0 | -12.4 |
| End ΔHead (deg) | 19.7 | 20.0 |
| Time El is < 0 (sec) (Sensor Breaklock) | 11.0 | 7.6 |

### Comments

The maneuver began with heading differences of 10° and the close was executed early. The parameters were still within tolerances.

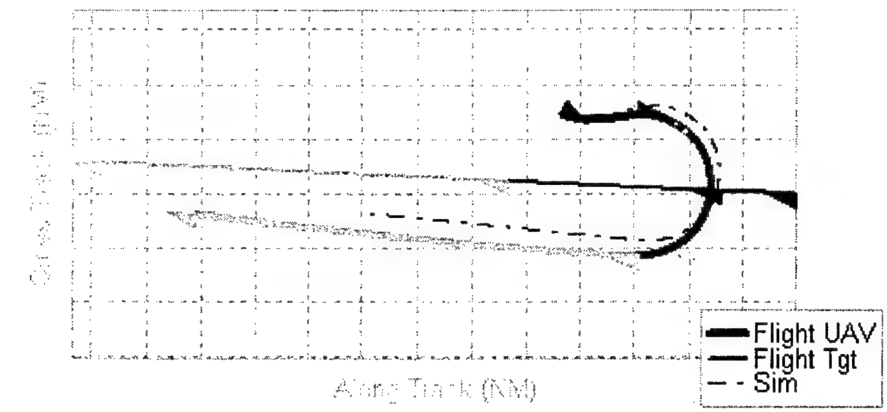
# Intercept 5

## $R_{min+15\%}$

Flight 2: 17 Oct 2003

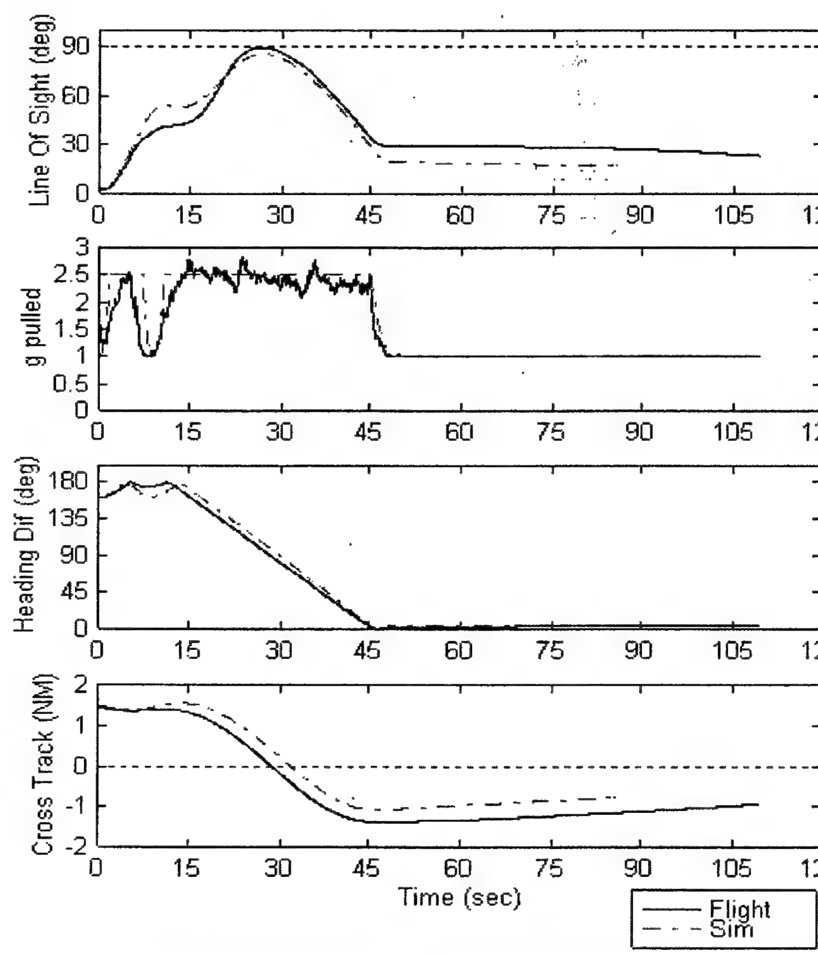
### Planned Intercept Parameters

Sensor: 90 / 90 (Az° / El°)
Initial Aspect: 160
Range at Open (NM): 4.6
UAV
Altitude (ft MSL): 27000
Planned Speed (TAS): 445
*Actual Avg Speed (TAS): 455*
Tanker
Altitude (ft MSL): 28000
Planned Speed (TAS): 417
*Actual Avg Speed (TAS): 411*




### Simulation/Flight Comparison

| Parameter | Sim | Flight |
|---|---|---|
| Initial Aspect (deg) | 161.5 | 160.9 |
| Horz Range (NM) | 4.6 | 4.6 |
| Success Criteria? | Yes | Yes |
| Max CT (NM) | 1.6 | 1.5 |
| Max LOS (deg) | 85.8 | 89.7 |
| Max Az (deg) | 51.1 | 36.6 |
| Max El (deg) | 81.0 | 85.3 |
| Min Range (NM) | 1.3 | 1.1 |
| End Range (NM) | 2.3 | 2.0 |
| End Aspect (NM) | -20.0 | -28.4 |
| End ΔHead (deg) | 3.7 | 5.3 |
| Time El is < 0 (sec) (Sensor Breaklock) | 7.5 | 6.2 |




### Comments

Maneuver on the edge of tolerances. A 9 KTAS faster test, 6 KTAS slower tanker, and slightly early close caused maneuver to be close to tolerances but still good. Sim and flight match well.

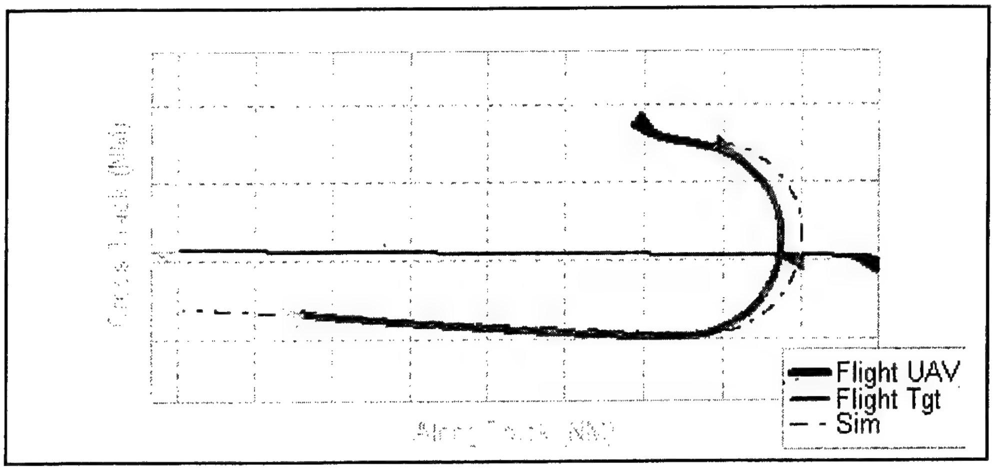
# Intercept 6 (Flight 1, Attempt 2)

## $R_{min+15\%}$

Flight 1: 8 Oct 2003

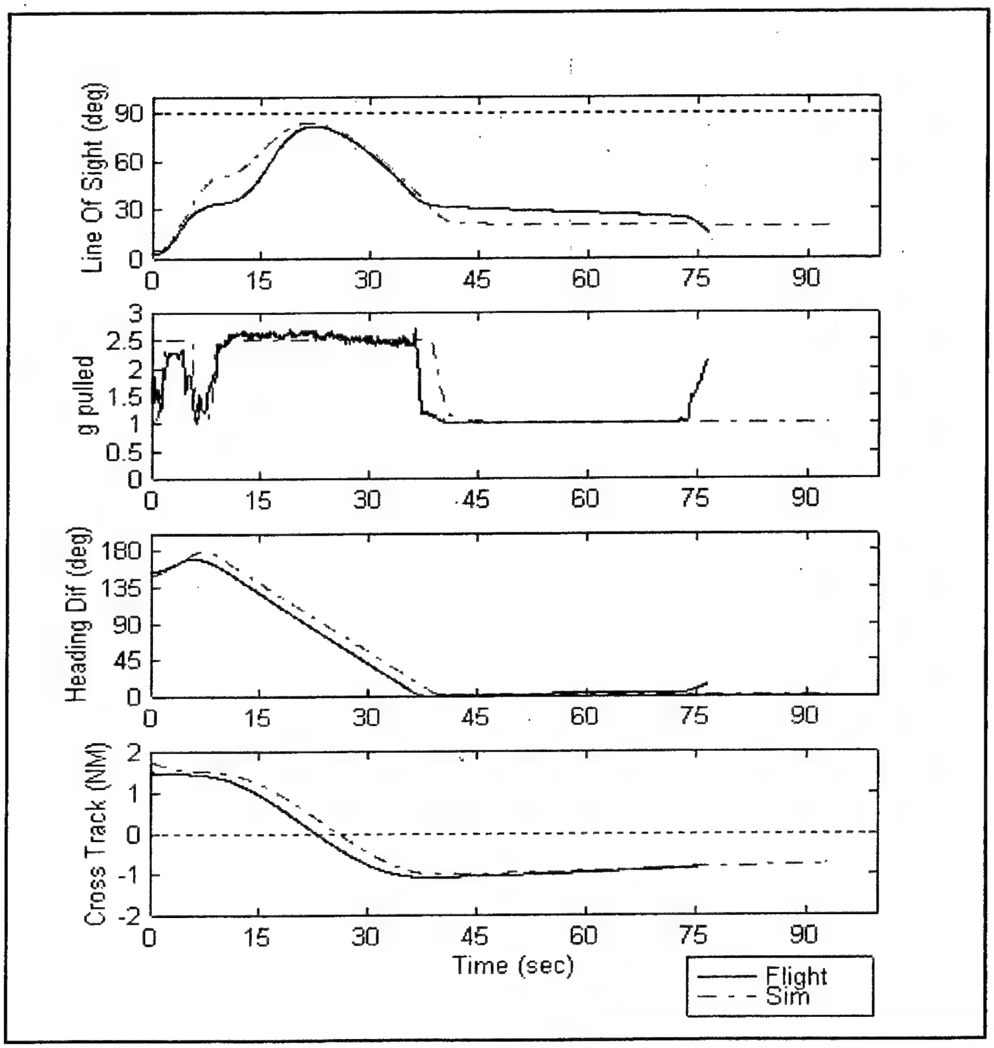
<u>Planned Intercept Parameters</u>

Sensor: 90 / 90 (Az° / El°)
Initial Aspect: 150
Range at Open (NM): 3.6
<u>UAV</u>
Altitude (ft MSL): 27000
Planned Speed (TAS): 445
*Actual Avg Speed (TAS): 444*
<u>Tanker</u>
Altitude (ft MSL): 28000
Planned Speed (TAS): 417
*Actual Avg Speed (TAS): 418*




<u>Simulation/Flight Comparison</u>

| Parameter | Sim | Flight |
|---|---|---|
| Initial Aspect (deg) | 150.9 | 155.3 |
| Horz Range (NM) | 3.6 | 3.6 |
| Success Criteria? | Yes | Yes |
| Max CT (NM) | 1.7 | 1.5 |
| Max LOS (deg) | 83.7 | 81.8 |
| Max Az (deg) | 43.6 | 28.8 |
| Max El (deg) | 81.1 | 80.4 |
| Min Range (NM) | 1.3 | 0.9 |
| End Range (NM) | 2.2 | 1.8 |
| End Aspect (NM) | -20.0 | -26.6 |
| End ΔHead (deg) | 2.4 | 14.3 |
| Time El is < 0 (sec) (Sensor Breaklock) | 5.3 | 4.1 |




<u>Comments</u>

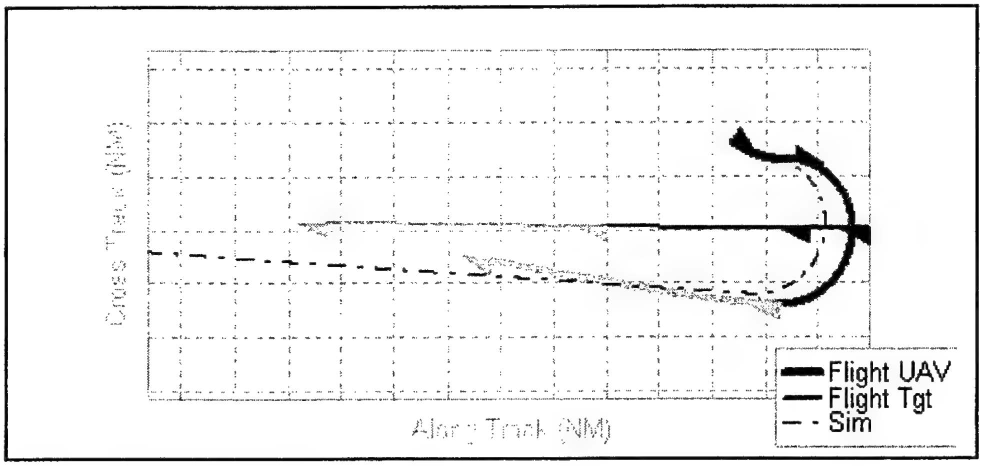
None.

# Intercept 7 (Flight 1)
## $R_{min}$

Flight 1: 8 Oct 2003

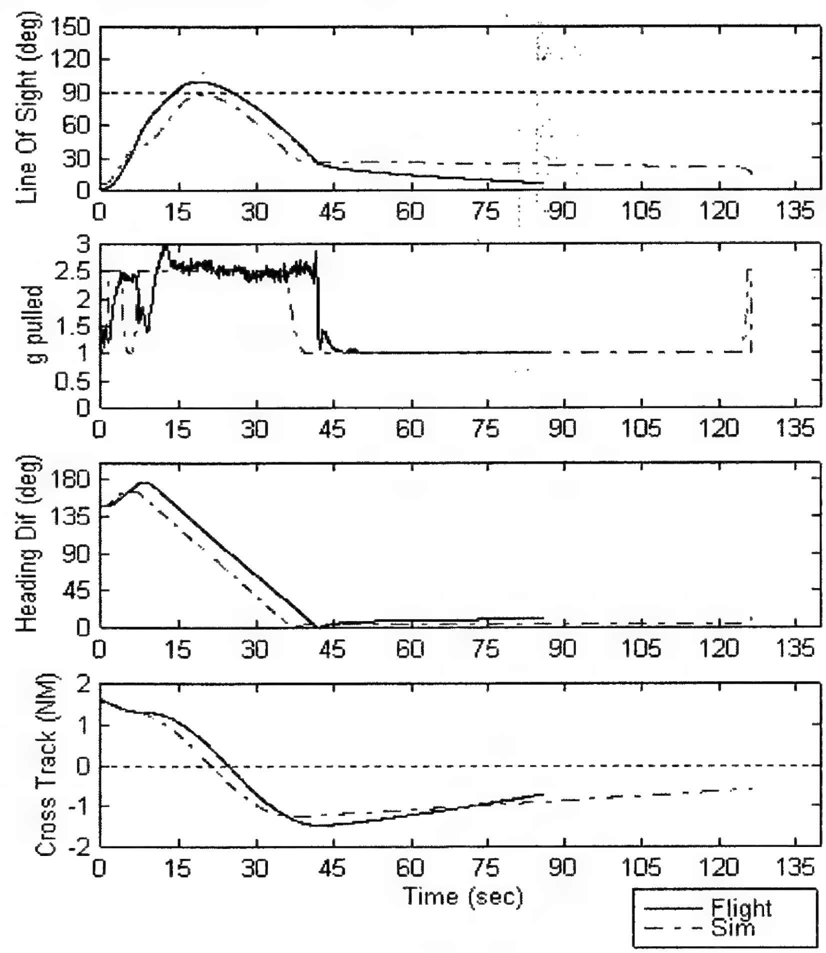
### Planned Intercept Parameters

Sensor: 90 / 90 (Az° / El°)
Initial Aspect: 150
Range at Open (NM): 3.1
UAV
Altitude (ft MSL): 27000
Planned Speed (TAS): 445
*Actual Avg Speed (TAS): 454*
Tanker
Altitude (ft MSL): 28000
Planned Speed (TAS): 417
*Actual Avg Speed (TAS): 426*




### Simulation/Flight Comparison

| Parameter | Sim | Flight |
|---|---|---|
| Initial Aspect (deg) | 147.8 | 149.1 |
| Horz Range (NM) | 3.1 | 3.1 |
| Success Criteria? | yes | no |
| Max CT (NM) | 1.6 | 1.6 |
| Max LOS (deg) | 88.4 | 100.1 |
| Max Az (deg) | 33.0 | 58.5 |
| Max El (deg) | 86.2 | 95.4 |
| Min Range (NM) | 1.0 | 1.2 |
| End Range (NM) | 1.7 | 3.2 |
| End Aspect (NM) | -20.0 | -12.8 |
| End ΔHead (deg) | 11.0 | 10.4 |
| Time El is < 0 (sec) (Sensor Breaklock) | 3.7 | 6.6 |




### Comments

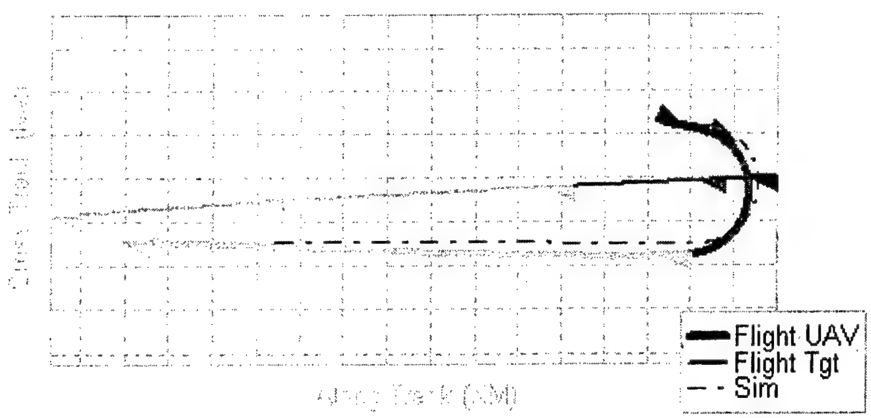
Flight intercept failed because the open was 15° to great delaying the close maneuver and causing excess line-of-sight. Showed how almost any maneuver deviation at $R_{min}$ will result in an unsuccessful intercept.

# Intercept 7 (Flight 2)
## $R_{min}$

Flight 2: 17 Oct 2003

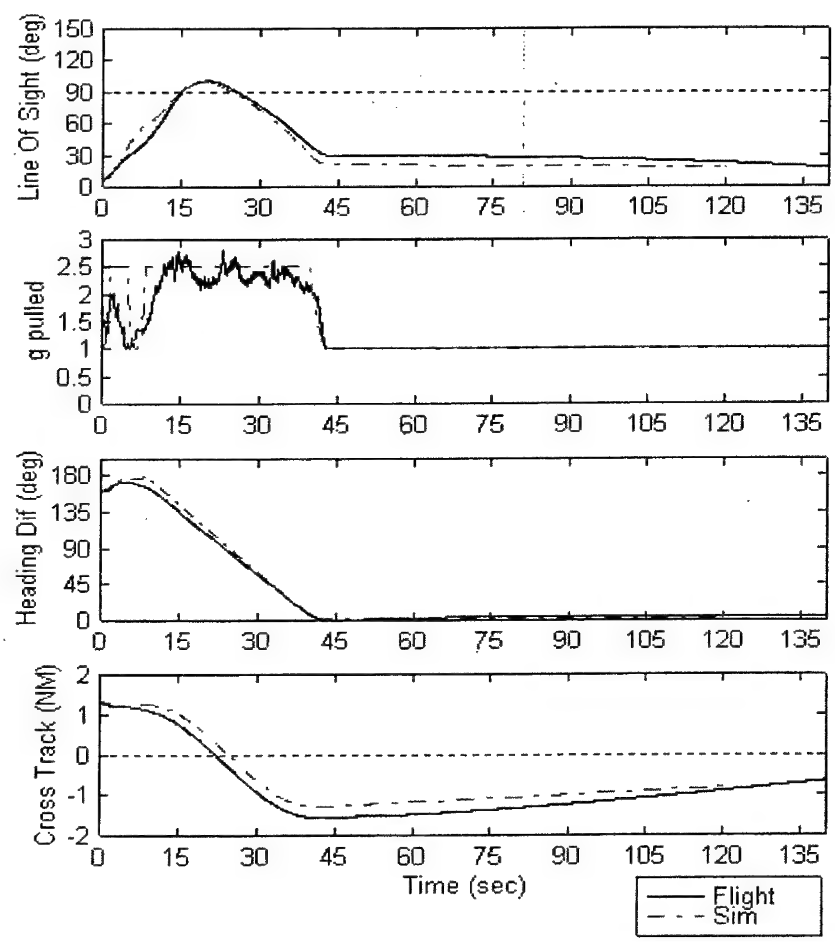
**Planned Intercept Parameters**

Sensor: 90 / 90 (Az° / El°)
Initial Aspect: 150
Range at Open (NM): 3.1
UAV
  Altitude (ft MSL): 27000
  Planned Speed (TAS): 445
  *Actual Avg Speed (TAS): 447*
Tanker
  Altitude (ft MSL): 28000
  Planned Speed (TAS): 417
  *Actual Avg Speed (TAS): 413*




**Simulation/Flight Comparison**

| Parameter | Sim | Flight |
|---|---|---|
| Initial Aspect (deg) | 154.1 | 155.1 |
| Horz Range (NM) | 3.1 | 3.1 |
| Success Criteria? | No | No |
| Max CT (NM) | 1.4 | 1.3 |
| Max LOS (deg) | 98.8 | 100.4 |
| Max Az (deg) | 50.7 | 46.9 |
| Max El (deg) | 93.4 | 95.0 |
| Min Range (NM) | 1.2 | 1.0 |
| End Range (NM) | 2.4 | 1.8 |
| End Aspect (NM) | -20.0 | -22.0 |
| End ΔHead (deg) | 2.8 | 5.2 |
| Time El is < 0 (sec) (Sensor Breaklock) | 5.7 | 4.0 |




**Comments**

A 155 initial aspect instead of 150 caused a 10° excursion in line-of-sight.

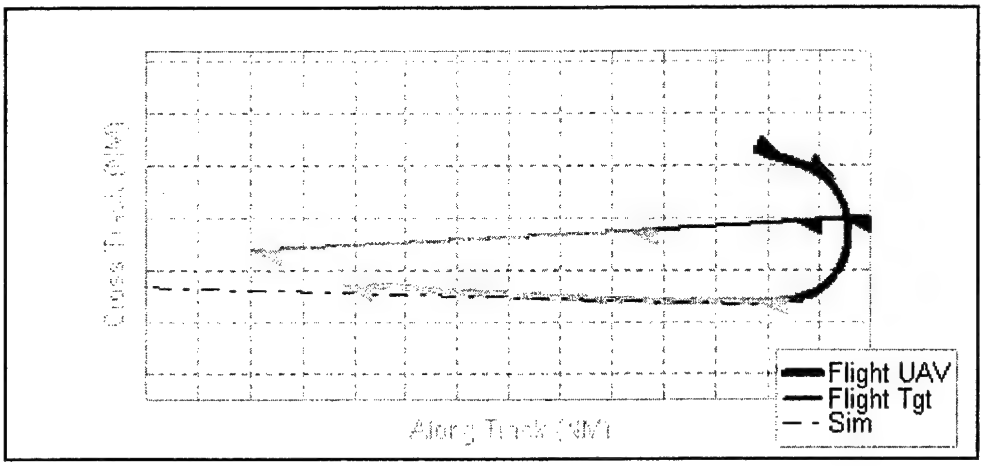
# Intercept 8

## $R_{min-15\%}$

Flight 2: 17 Oct 2003

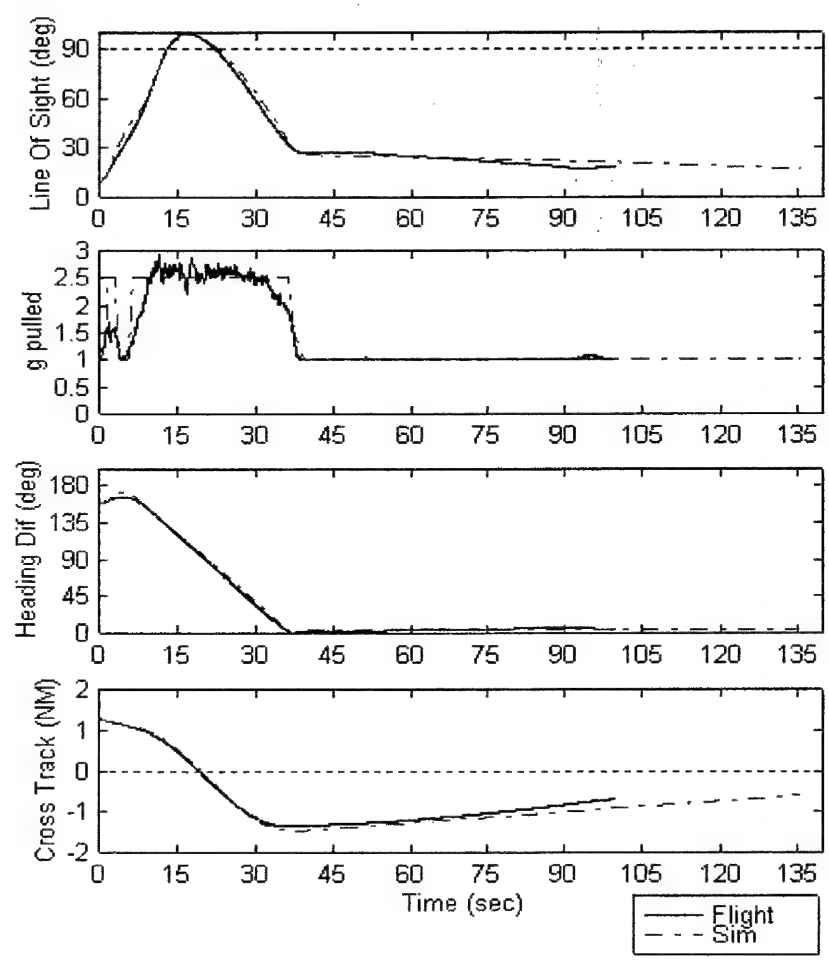
### Planned Intercept Parameters

Sensor: 90 / 90 (Az° / El°)
Initial Aspect: 150
Range at Open (NM): 2.6
UAV
Altitude (ft MSL): 27000
Planned Speed (TAS): 445
*Actual Avg Speed (TAS): 452*
Tanker
Altitude (ft MSL): 28000
Planned Speed (TAS): 417
*Actual Avg Speed (TAS): 416*




### Simulation/Flight Comparison

| Parameter | Sim | Flight |
|---|---|---|
| Initial Aspect (deg) | 150.0 | 151.0 |
| Horz Range (NM) | 2.6 | 2.6 |
| Success Criteria? | No | No |
| Max CT (NM) | 1.3 | 1.3 |
| Max LOS (deg) | 99.4 | 99.6 |
| Max Az (deg) | 38.0 | 43.5 |
| Max El (deg) | 94.2 | 96.2 |
| Min Range (NM) | 0.9 | 0.9 |
| End Range (NM) | 1.8 | 1.9 |
| End Aspect (NM) | -20.0 | -21.5 |
| End ΔHead (deg) | 4.1 | 4.1 |
| Time El is < 0 (sec) (Sensor Breaklock) | 3.8 | 3.3 |




### Comments

Very good match.

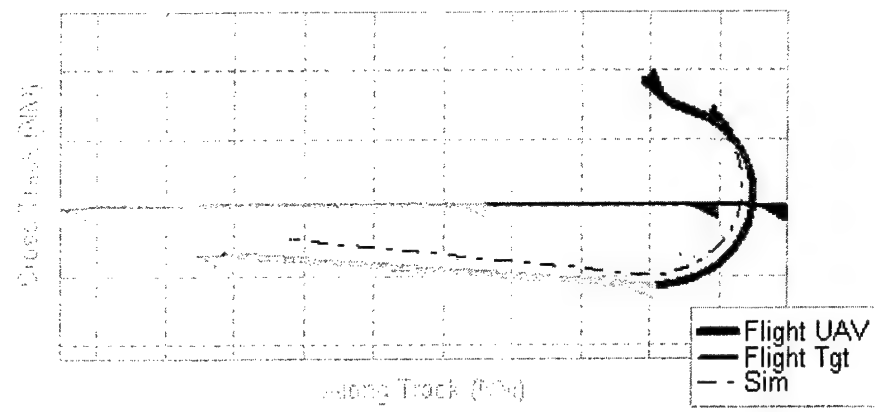
# Intercept 9

## $R_{min+15\%}$

Flight 3: 28 Oct 2003

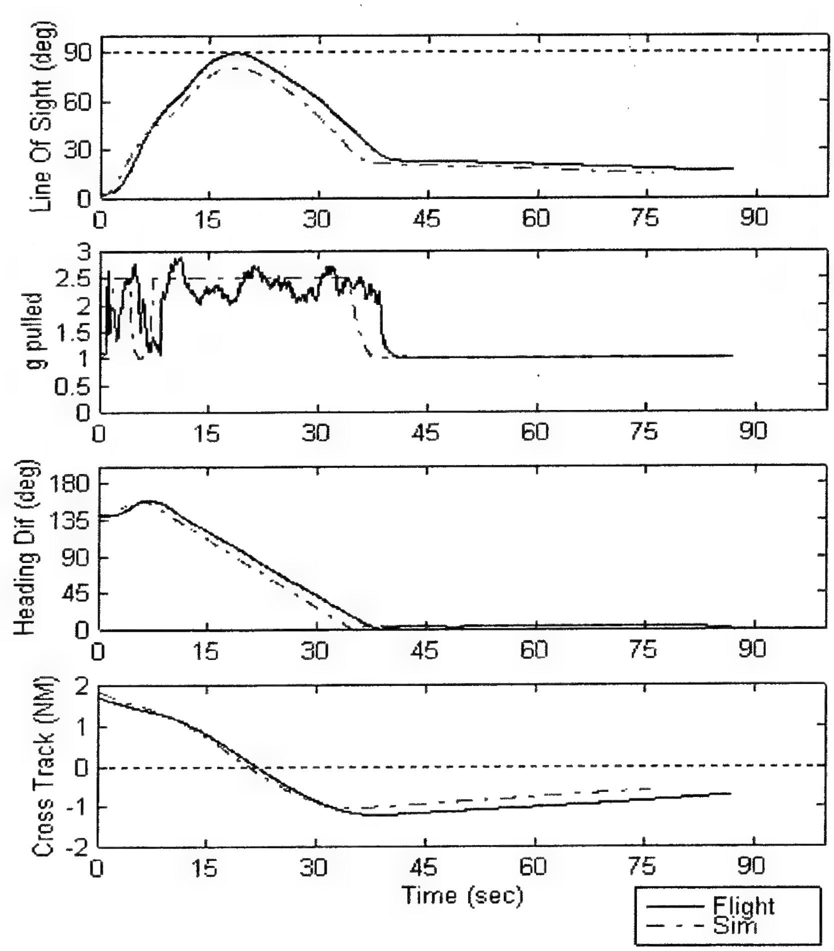
Planned Intercept Parameters

Sensor: 90 / 90 (Az° / El°)
Initial Aspect: 140
Range at Open (NM): 2.8
UAV
Altitude (ft MSL): 27000
Planned Speed (TAS): 445
*Actual Avg Speed (TAS): 449*
Tanker
Altitude (ft MSL): 28000
Planned Speed (TAS): 417
*Actual Avg Speed (TAS): 405*




Simulation/Flight Comparison

| Parameter | Sim | Flight |
|---|---|---|
| Initial Aspect (deg) | 138.3 | 142.0 |
| Horz Range (NM) | 2.8 | 2.8 |
| Success Criteria? | Yes | Yes |
| Max CT (NM) | 1.9 | 1.7 |
| Max LOS (deg) | 80.6 | 89.8 |
| Max Az (deg) | 36.8 | 42.9 |
| Max El (deg) | 75.7 | 83.9 |
| Min Range (NM) | 1.1 | 1.2 |
| End Range (NM) | 1.7 | 2.1 |
| End Aspect (NM) | -20.0 | -20.0 |
| End ΔHead (deg) | 5.3 | 2.8 |
| Time El is <.0 (sec) (Sensor Breaklock) | 4.4 | 4.7 |



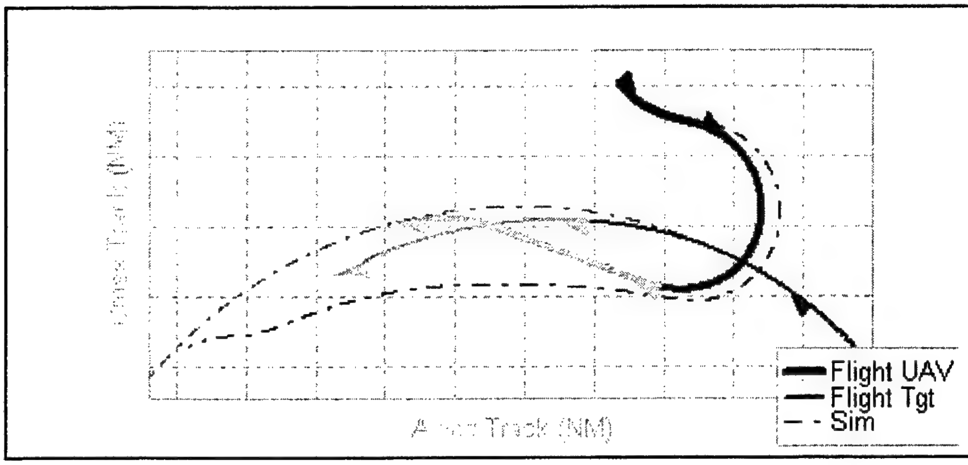

Comments

None.

# Intercept 10

## $R_{min+15\%}$

Flight 1: 8 Oct 2003

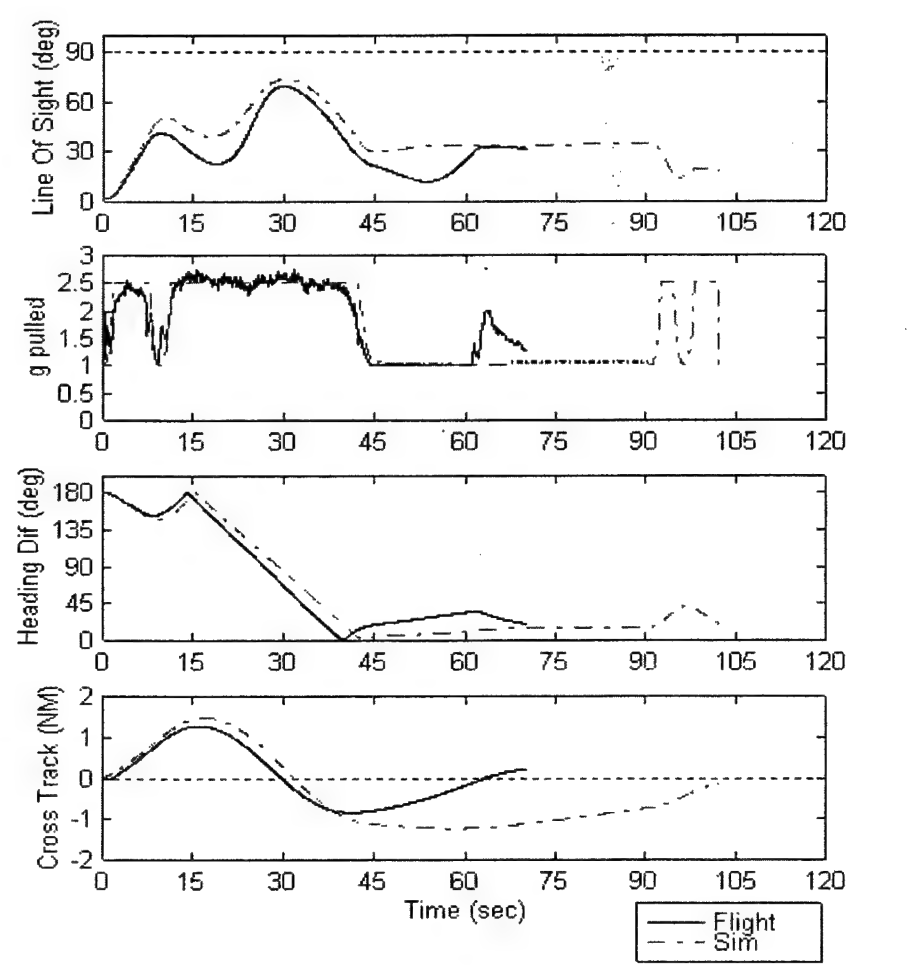



### Planned Intercept Parameters

Sensor: 90 / 90 (Az° / El°)
Initial Aspect: 180
Range at Open (NM): 5.5
UAV
Altitude (ft MSL): 27000
Planned Speed (TAS): 445
*Actual Avg Speed (TAS): 446*
Tanker
Altitude (ft MSL): 28000
Planned Speed (TAS): 417
*Actual Avg Speed (TAS): 421*

### Simulation/Flight Comparison

| Parameter | Sim | Flight |
|---|---|---|
| Initial Aspect (deg) | -179.7 | -179.7 |
| Horz Range (NM) | 5.5 | 5.5 |
| Success Criteria? | No | Yes |
| Max CT (NM) | 1.5 | 1.3 |
| Max LOS (deg) | 74.0 | 69.7 |
| Max Az (deg) | 49.7 | 40.3 |
| Max El (deg) | 71.0 | 68.4 |
| Min Range (NM) | 0.7 | 0.7 |
| End Range (NM) | 0.7 | 1.1 |
| End Aspect (NM) | -10.9 | 11.5 |
| End ΔHead (deg) | 19.6 | 20.0 |
| Time El is < 0 (sec) (Sensor Breaklock) | 42.9 | 7.1 |




### Comments

Slightly early close maneuver—0.3 NM along track difference from planned. After closing, UAV deviated from planned maneuver by cutting to tail aspect early (more operational but less efficient). This was a flight test, not a UAV issue. Tanker maneuvering logic needs to be refined.

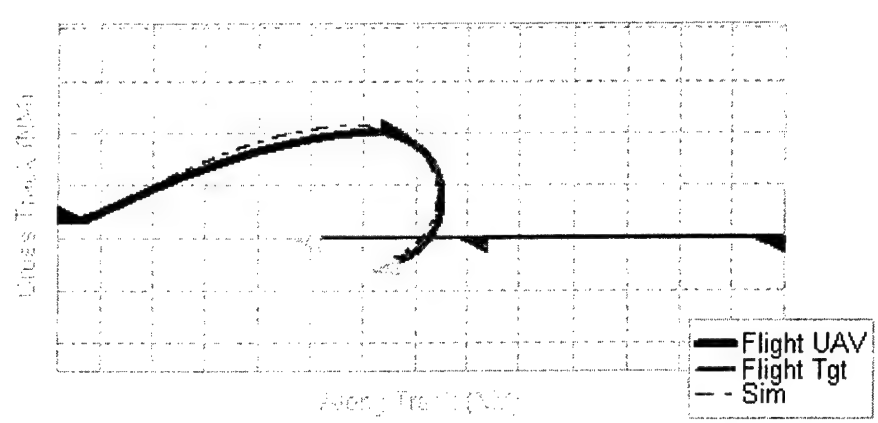
# Intercept 12

## $R_{min+15\%}$

Flight 2: 17 Oct 2003

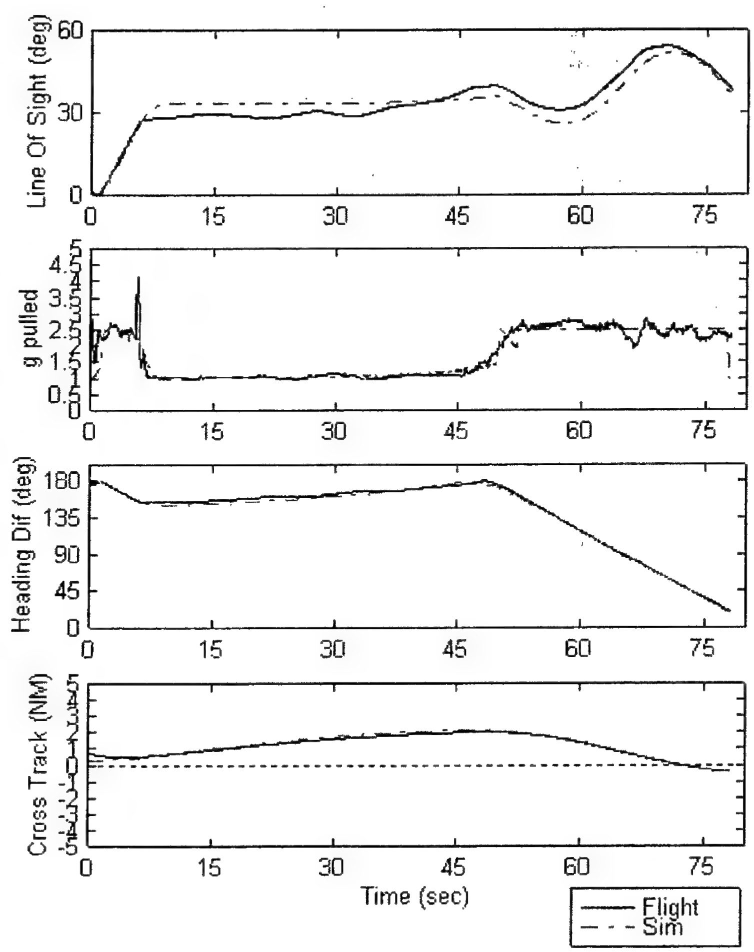
### Planned Intercept Parameters

Sensor: 40 / 70 (Az° / El°)
Initial Aspect: 180
Range at Open (NM): 13.8
UAV
Altitude (ft MSL): 20000
Planned Speed (TAS): 445
*Actual Avg Speed (TAS): 449*
Tanker
Altitude (ft MSL): 21000
Planned Speed (TAS): 417
*Actual Avg Speed (TAS): 413*




### Simulation/Flight Comparison

| Parameter | Sim | Flight |
|---|---|---|
| Initial Aspect (deg) | 178.7 | 176.9 |
| Horz Range (NM) | 13.8 | 13.8 |
| Success Criteria? | Yes | Yes |
| Max CT (NM) | 2.1 | 2.0 |
| Max LOS (deg) | 51.8 | 54.0 |
| Max Az (deg) | 33.1 | 34.1 |
| Max El (deg) | 49.9 | 53.4 |
| Min Range (NM) | 1.1 | 1.1 |
| End Range (NM) | 1.4 | 1.5 |
| End Aspect (NM) | -17.0 | -17.1 |
| End ΔHead (deg) | 19.6 | 19.8 |
| Time El is < 0 (sec) (Sensor Breaklock) | 7.3 | 5.7 |




### Comments

None.

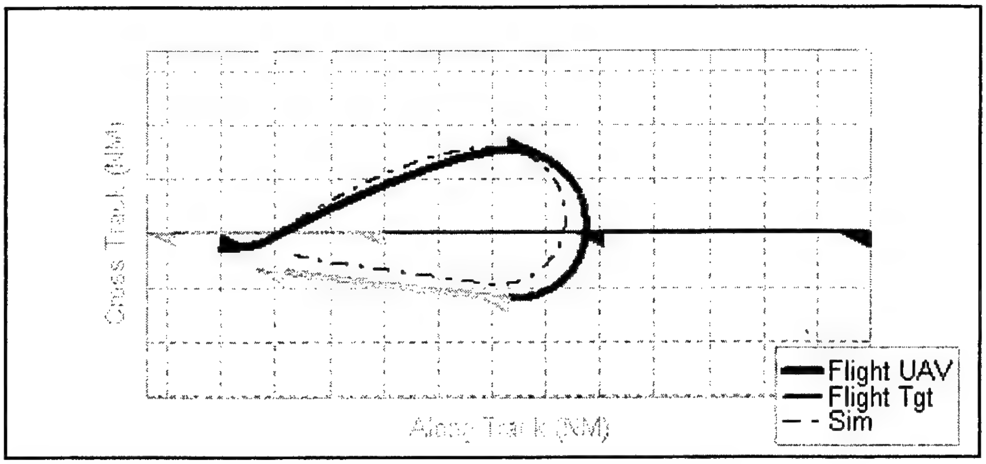
# Intercept 13 (Flight 2)
## $R_{min}$

Flight 2: 17 Oct 2003

**Planned Intercept Parameters**

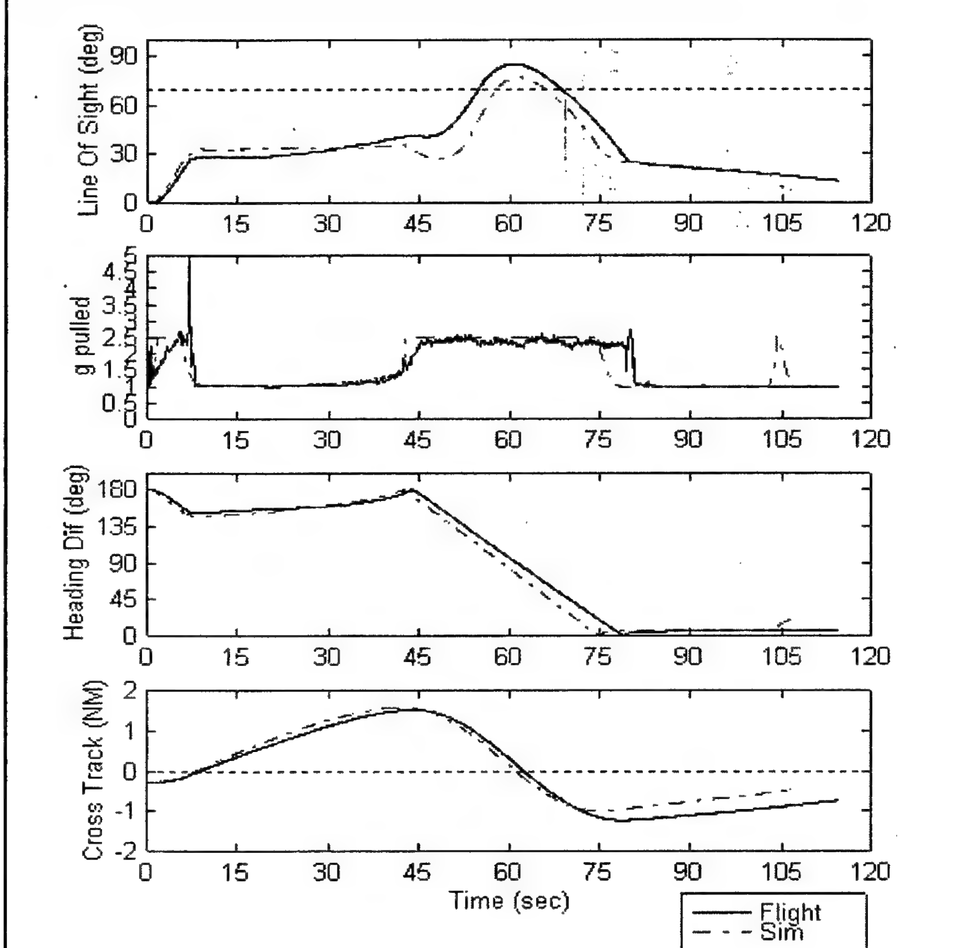
Sensor: 40 / 70 (Az° / El°)
Initial Aspect: 180
Range at Open (NM): 12.0
UAV
- Altitude (ft MSL): 20000
- Planned Speed (TAS): 445
- *Actual Avg Speed (TAS): 449*

Tanker
- Altitude (ft MSL): 21000
- Planned Speed (TAS): 417
- *Actual Avg Speed (TAS): 414*




**Simulation/Flight Comparison**

| Parameter | Sim | Flight |
|---|---|---|
| Initial Aspect (deg) | -178.7 | -178.7 |
| Horz Range (NM) | 12.0 | 12.0 |
| Success Criteria? | No | No |
| Max CT (NM) | 1.6 | 1.5 |
| Max LOS (deg) | 76.9 | 84.9 |
| Max Az (deg) | 33.1 | 32.6 |
| Max El (deg) | 73.6 | 82.1 |
| Min Range (NM) | 0.9 | 1.1 |
| End Range (NM) | 1.4 | 2.2 |
| End Aspect (NM) | -19.9 | -20.0 |
| End ΔHead (deg) | 19.0 | 7.5 |
| Time El is < 0 (sec) (Sensor Breaklock) | 7.1 | 6.0 |




**Comments**

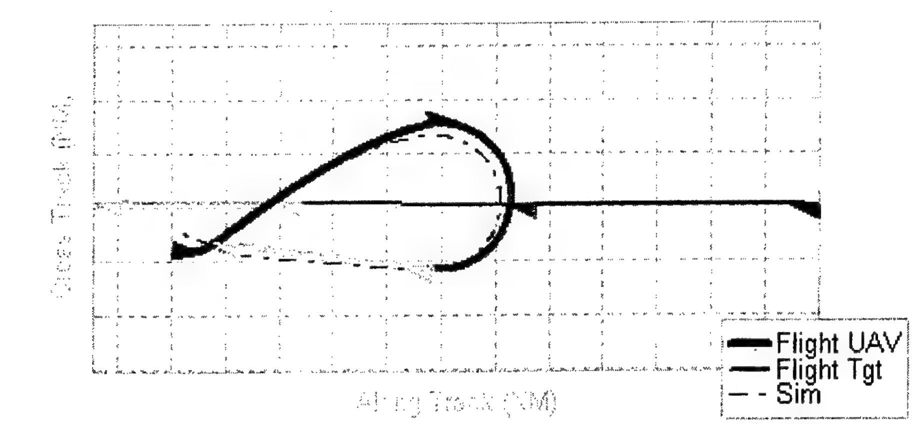
Slight heading and airspeed errors in flight cause unsuccessful rejoin. Simulation and flight data match well. $R_{min}$ very sensitive to slight errors.

# Intercept 13 (Flight 2, Attempt 2)
## $R_{min}$

Flight 2: 17 Oct 2003

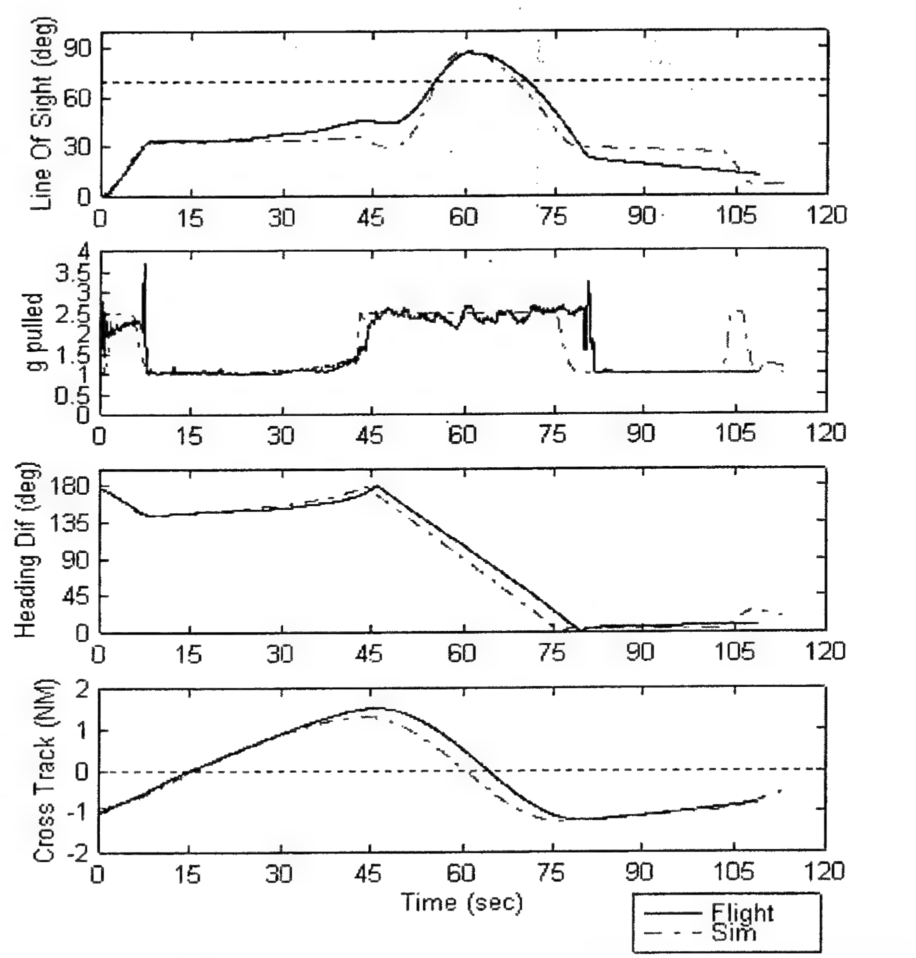
### Planned Intercept Parameters

Sensor: 40 / 70 (Az° / El°)
Initial Aspect: 180
Range at Open (NM): 12.0
UAV
  Altitude (ft MSL): 20000
  Planned Speed (TAS): 445
  *Actual Avg Speed (TAS): 447*
Tanker
  Altitude (ft MSL): 21000
  Planned Speed (TAS): 417
  *Actual Avg Speed (TAS): 419*




### Simulation/Flight Comparison

| Parameter | Sim | Flight |
|---|---|---|
| Initial Aspect (deg) | -175.7 | -175.0 |
| Horz Range (NM) | 12.0 | 12.0 |
| Success Criteria? | No | No |
| Max CT (NM) | 1.3 | 1.5 |
| Max LOS (deg) | 88.4 | 86.6 |
| Max Az (deg) | 33.1 | 37.8 |
| Max El (deg) | 84.7 | 82.9 |
| Min Range (NM) | 0.8 | 1.2 |
| End Range (NM) | 1.7 | 2.3 |
| End Aspect (NM) | -18.8 | -20.0 |
| End ΔHead (deg) | 19.9 | 8.4 |
| Time El is < 0 (sec) (Sensor Breaklock) | 7.2 | 7.3 |



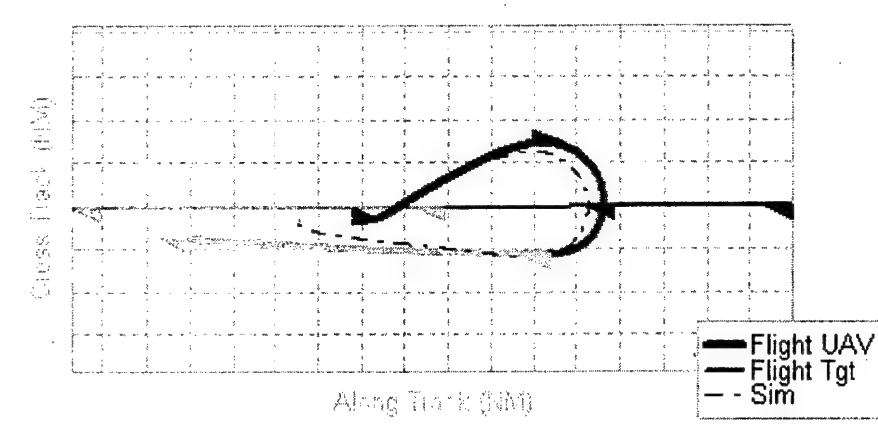

### Comments

Initial aspect was off (almost 1 NM on tanker left). Open maneuver to opposite side of tanker caused unsuccessful intercept due to line-of-sight overshoots.

# Intercept 14 (Flight 2)

## $R_{min-15\%}$

Flight 2: 17 Oct 2003




## Planned Intercept Parameters

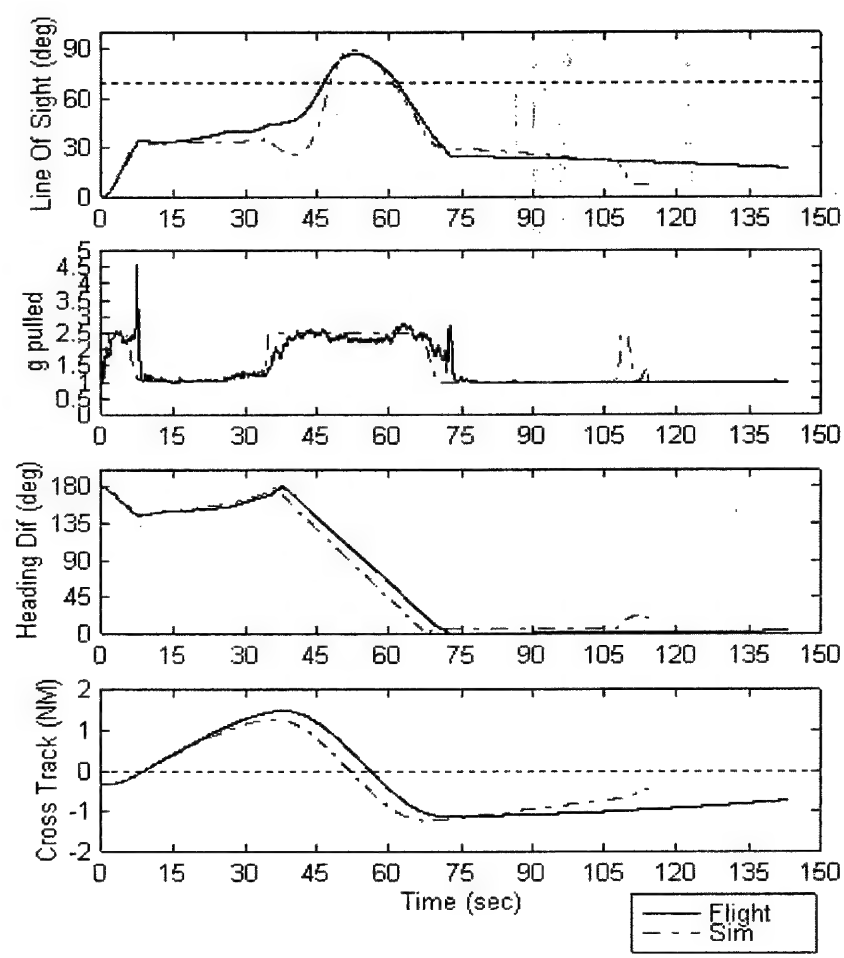
Sensor: 40 / 70 (Az° / El°)
Initial Aspect: 180
Range at Open (NM): 10.2

UAV
- Altitude (ft MSL): 20000
- Planned Speed (TAS): 445
- *Actual Avg Speed (TAS): 443*

Tanker
- Altitude (ft MSL): 21000
- Planned Speed (TAS): 417
- *Actual Avg Speed (TAS): 414*

## Simulation/Flight Comparison

| Parameter | Sim | Flight |
|---|---|---|
| Initial Aspect (deg) | -178.0 | -178.0 |
| Horz Range (NM) | 10.2 | 10.2 |
| Success Criteria? | No | No |
| Max CT (NM) | 1.3 | 1.5 |
| Max LOS (deg) | 89.3 | 87.1 |
| Max Az (deg) | 33.1 | 37.7 |
| Max El (deg) | 85.8 | 83.0 |
| Min Range (NM) | 0.7 | 1.2 |
| End Range (NM) | 1.4 | 2.1 |
| End Aspect (NM) | -18.3 | -20.0 |
| End ΔHead (deg) | 19.8 | 3.3 |
| Time El is < 0 (sec) (Sensor Breaklock) | 6.9 | 7.1 |




## Comments

None.

# Intercept 14 (Flight 2, Attempt 2)

## $R_{min-15\%}$

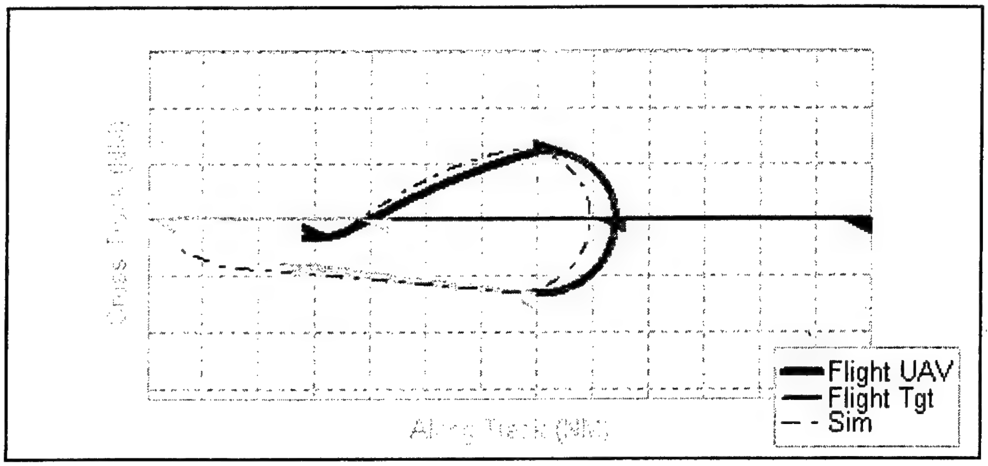
Flight 2: 17 Oct 2003

### Planned Intercept Parameters

Sensor: 40 / 70 (Az° / El°)
Initial Aspect: 180
Range at Open (NM): 10.2

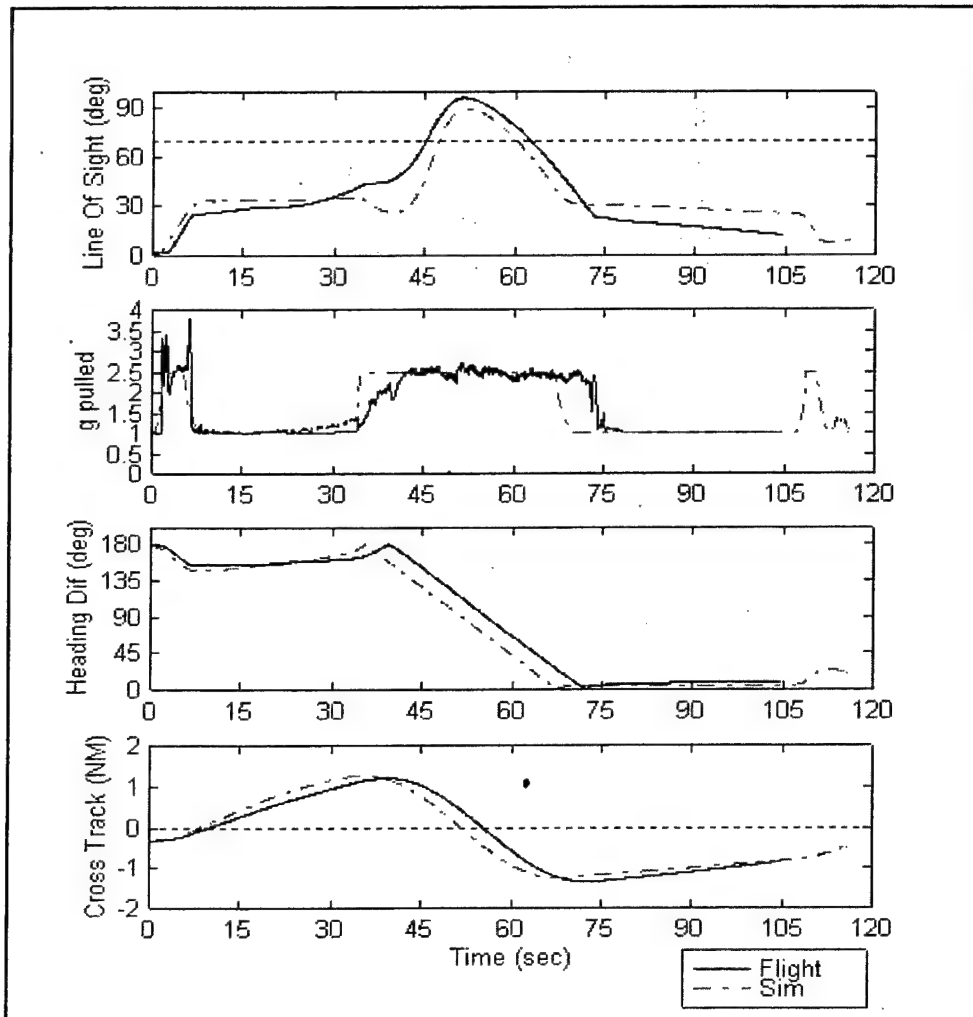
UAV
- Altitude (ft MSL): 20000
- Planned Speed (TAS): 445
- *Actual Avg Speed (TAS): 445*

Tanker
- Altitude (ft MSL): 21000
- Planned Speed (TAS): 417
- *Actual Avg Speed (TAS): 420*




### Simulation/Flight Comparison

| Parameter | Sim | Flight |
|---|---|---|
| Initial Aspect (deg) | -178.2 | -178.2 |
| Horz Range (NM) | 10.2 | 10.2 |
| Success Criteria? | No | No |
| Max CT (NM) | 1.3 | 1.2 |
| Max LOS (deg) | 89.4 | 96.2 |
| Max Az (deg) | 33.1 | 38.0 |
| Max El (deg) | 86.3 | 93.5 |
| Min Range (NM) | 0.7 | 1.0 |
| End Range (NM) | 1.5 | 2.5 |
| End Aspect (NM) | -18.5 | -20.0 |
| End ΔHead (deg) | 19.9 | 8.8 |
| Time El is < 0 (sec) (Sensor Breaklock) | 7.1 | 4.8 |




### Comments

None.

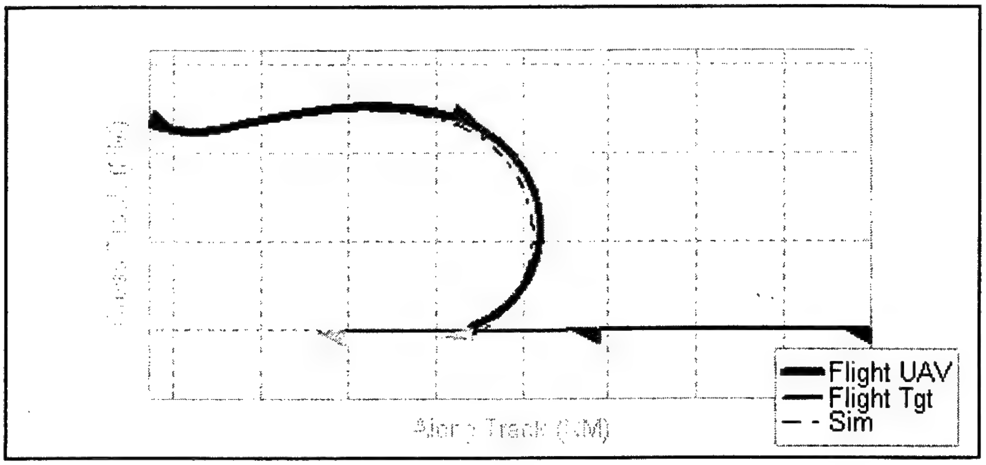
# Intercept 15 (Flight 2, Attempt 2)

## R $_{min+15\%}$

Flight 2: 17 Oct 2003

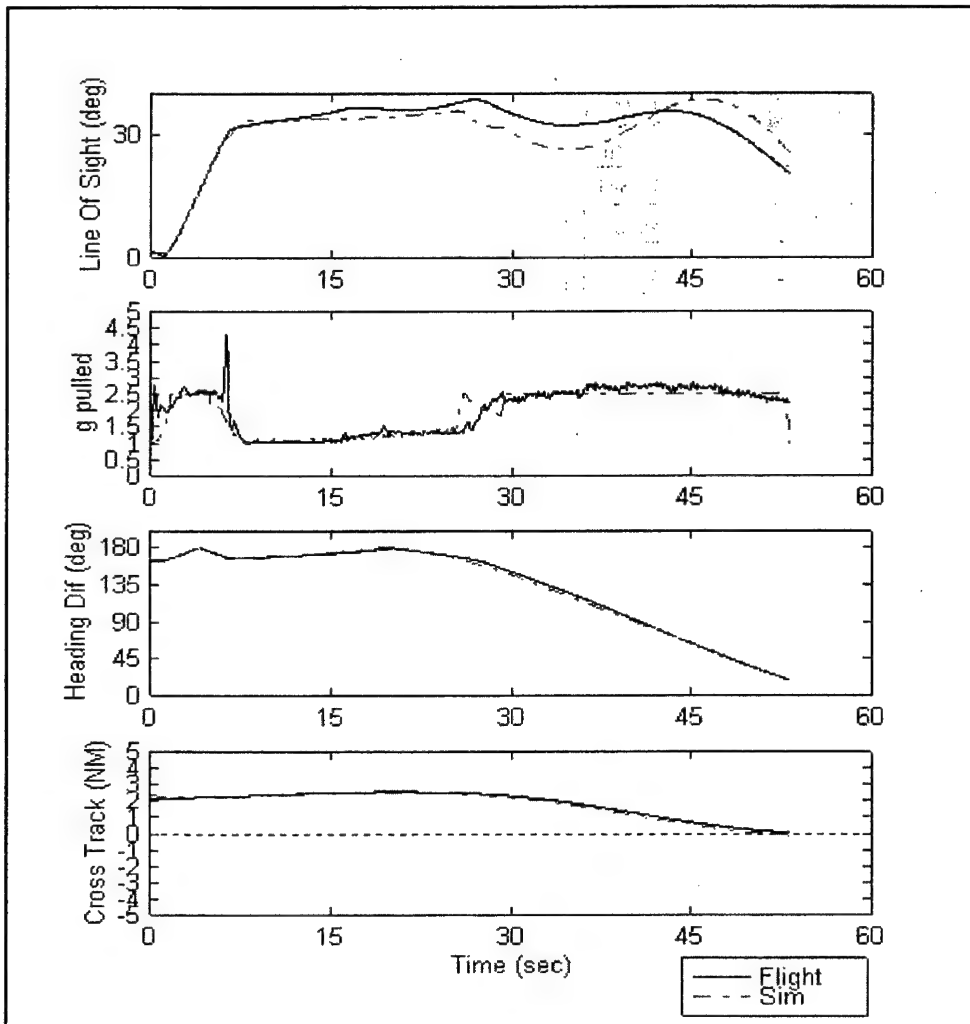
### Planned Intercept Parameters

Sensor: 40 / 70 (Az° / El°)
Initial Aspect: 170
Range at Open (NM): 8.6
UAV
Altitude (ft MSL): 20000
Planned Speed (TAS): 445
*Actual Avg Speed (TAS): 451*
Tanker
Altitude (ft MSL): 21000
Planned Speed (TAS): 417
*Actual Avg Speed (TAS): 418*




### Simulation/Flight Comparison

| Parameter | Sim | Flight |
|---|---|---|
| Initial Aspect (deg) | 164.3 | 166.0 |
| Horz Range (NM) | 8.6 | 8.6 |
| Success Criteria? | Yes | Yes |
| Max CT (NM) | 2.5 | 2.5 |
| Max LOS (deg) | 38.5 | 38.6 |
| Max Az (deg) | 33.4 | 34.2 |
| Max El (deg) | 37.7 | 35.7 |
| Min Range (NM) | 1.2 | 1.2 |
| End Range (NM) | 1.3 | 1.4 |
| End Aspect (NM) | -5.0 | 2.1 |
| End ΔHead (deg) | 19.7 | 19.6 |
| Time El is < 0 (sec) (Sensor Breaklock) | 6.6 | 5.7 |




### Comments

None.

# Intercept 16

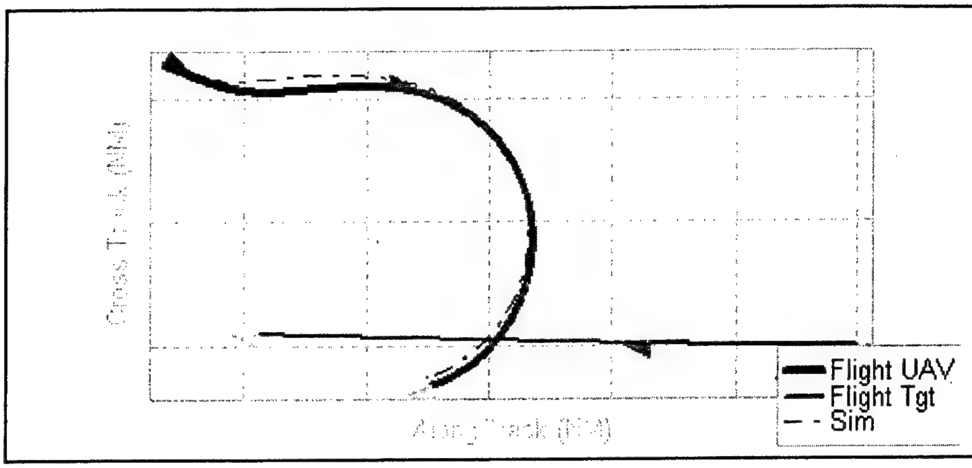
## $R_{min+15\%}$

Flight 3: 28 Oct 2003

### Planned Intercept Parameters

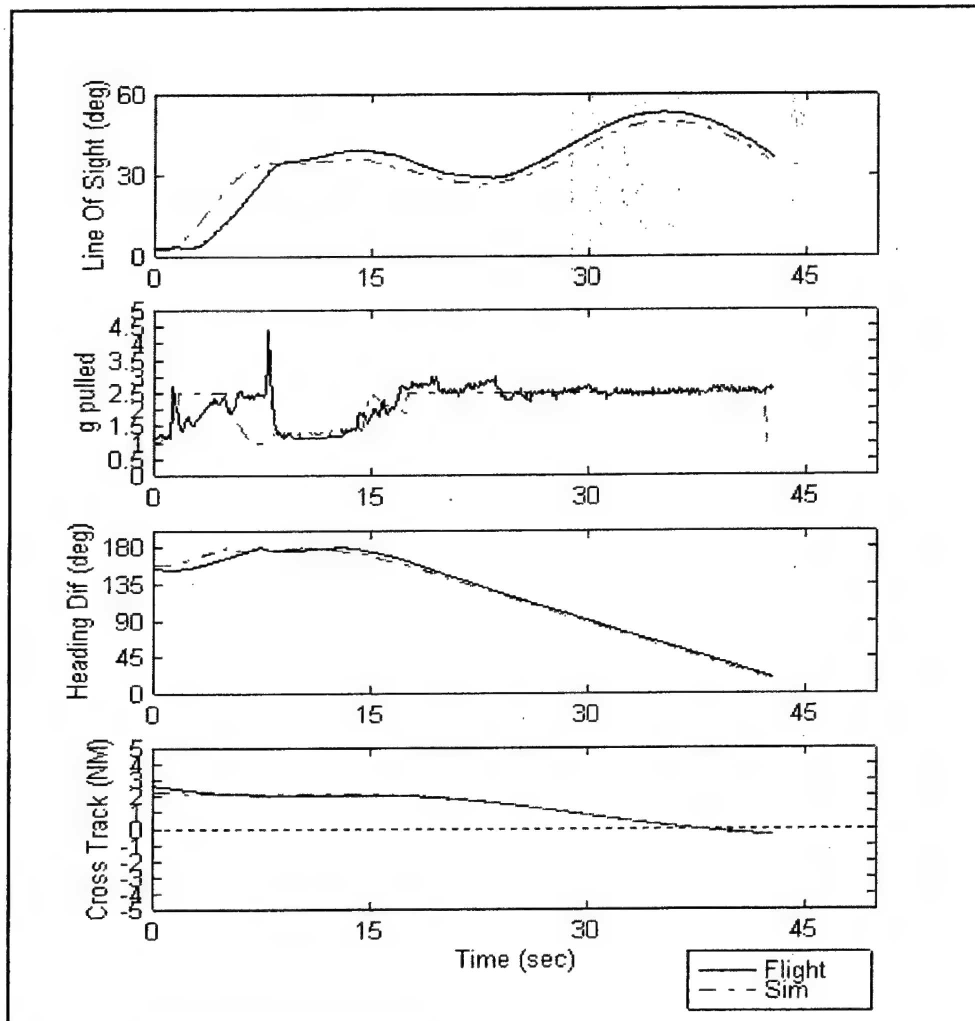
Sensor: 40 / 70 (Az° / El°)
Initial Aspect: 160
Range at Open (NM): 6.1
UAV
- Altitude (ft MSL): 20000
- Planned Speed (TAS): 445
- *Actual Avg Speed (TAS): 448*

Tanker
- Altitude (ft MSL): 21000
- Planned Speed (TAS): 417
- *Actual Avg Speed (TAS): 411*




### Simulation/Flight Comparison

| Parameter | Sim | Flight |
|---|---|---|
| Initial Aspect (deg) | 157.9 | 154.1 |
| Horz Range (NM) | 6.1 | 6.1 |
| Success Criteria? | Yes | Yes |
| Max CT (NM) | 2.3 | 2.7 |
| Max LOS (deg) | 49.9 | 53.2 |
| Max Az (deg) | 33.8 | 34.3 |
| Max El (deg) | 49.8 | 52.8 |
| Min Range (NM) | 1.1 | 1.1 |
| End Range (NM) | 1.3 | 1.5 |
| End Aspect (NM) | -14.8 | -15.9 |
| End ΔHead (deg) | 19.5 | 19.6 |
| Time El is < 0 (sec) (Sensor Breaklock) | 5.9 | 5.4 |




### Comments

None.

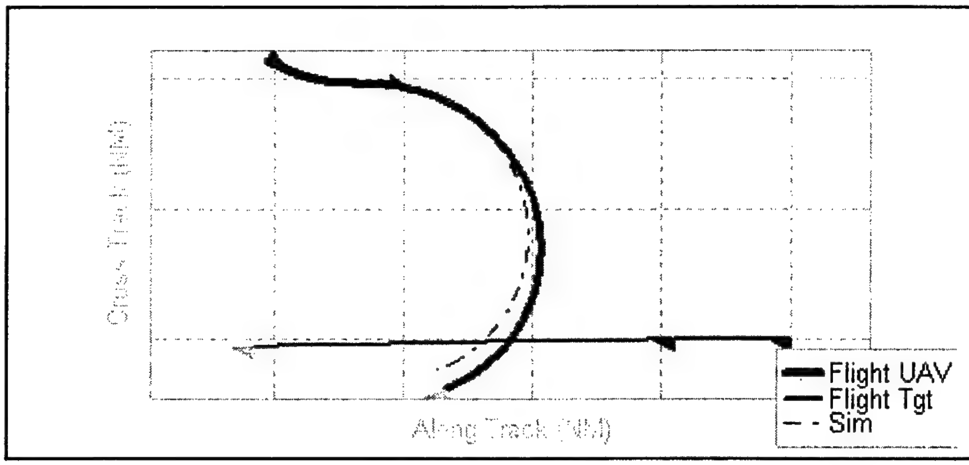
# Intercept 17 (Flight 1)

## $R_{min+15\%}$

Flight 1: 8 Oct 2003

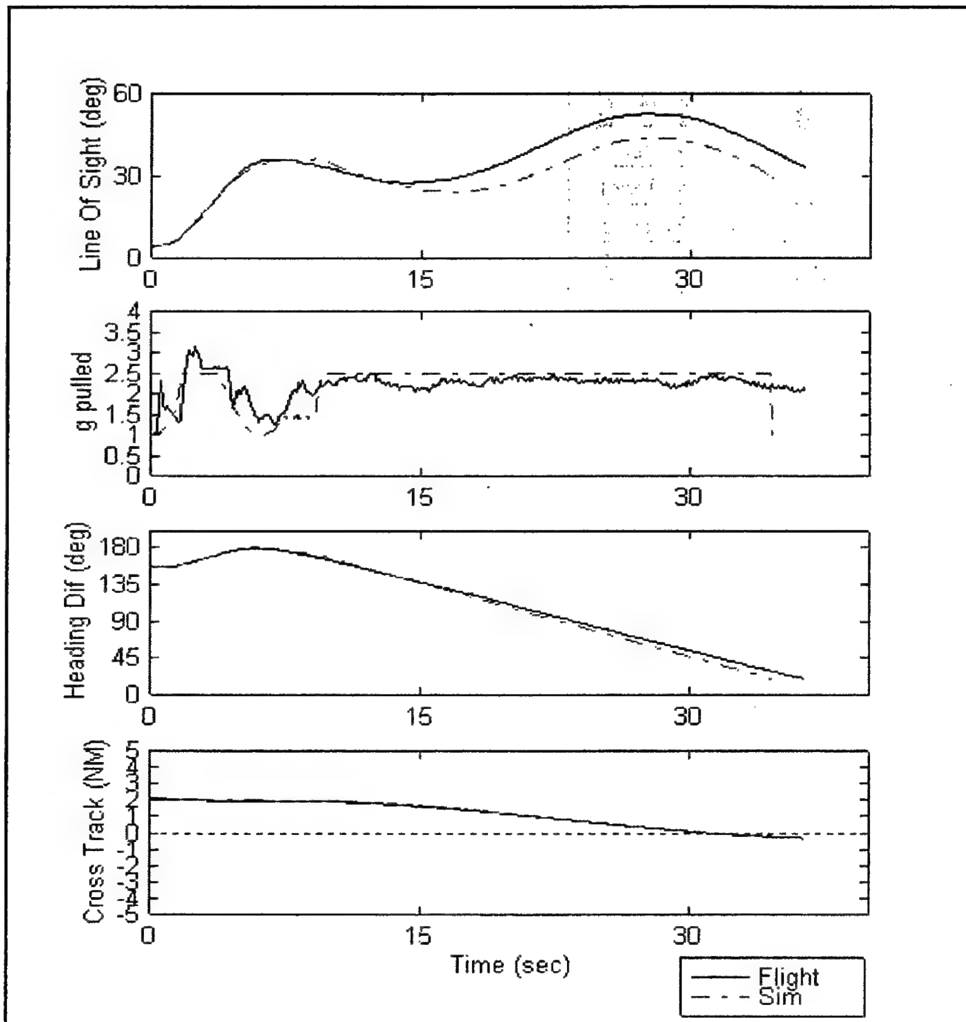
### Planned Intercept Parameters

Sensor: 40 / 70 (Az° / El°)
Initial Aspect: 150
Range at Open (NM): 4.6
UAV
  Altitude (ft MSL): 27000
  Planned Speed (TAS): 445
  *Actual Avg Speed (TAS): 417*
Tanker
  Altitude (ft MSL): 28000
  Planned Speed (TAS): 417
  *Actual Avg Speed (TAS): 419*




### Simulation/Flight Comparison

| Parameter | Sim | Flight |
|---|---|---|
| Initial Aspect (deg) | 152.2 | 152.7 |
| Horz Range (NM) | 4.6 | 4.6 |
| Success Criteria? | Yes | Yes |
| Max CT (NM) | 2.1 | 2.1 |
| Max LOS (deg) | 44.0 | 52.5 |
| Max Az (deg) | 34.2 | 34.9 |
| Max El (deg) | 43.7 | 50.6 |
| Min Range (NM) | 1.0 | 1.1 |
| End Range (NM) | 1.2 | 1.5 |
| End Aspect (NM) | -8.5 | -12.7 |
| End ΔHead (deg) | 19.6 | 19.7 |
| Time El is < 0 (sec) (Sensor Breaklock) | 5.2 | 4.7 |




### Comments

UAV flew off conditions (416 KTAS) and at average g of 2.2 instead of 2.5. Despite this, the turn radius was similar to desired. Very little open was required because most cross-track is from initial aspect—an "easier" and more tolerant condition.

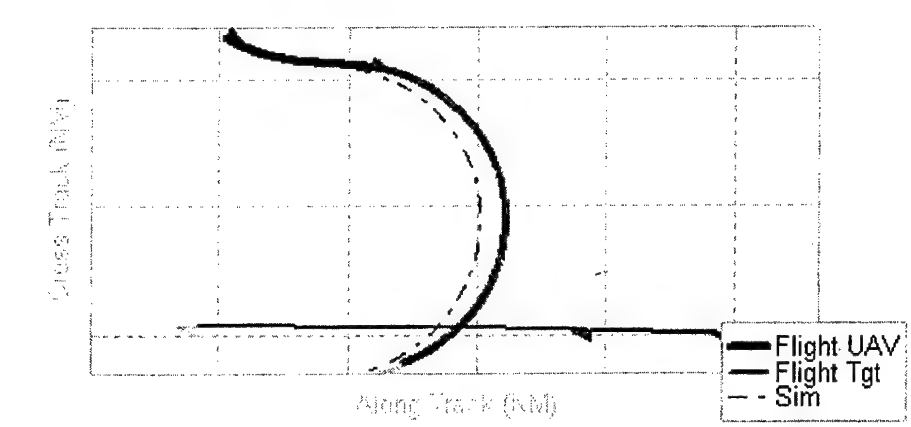
# Intercept 17 (Flight 2)

## $R_{min+15\%}$

Flight 2: 17 Oct 2003

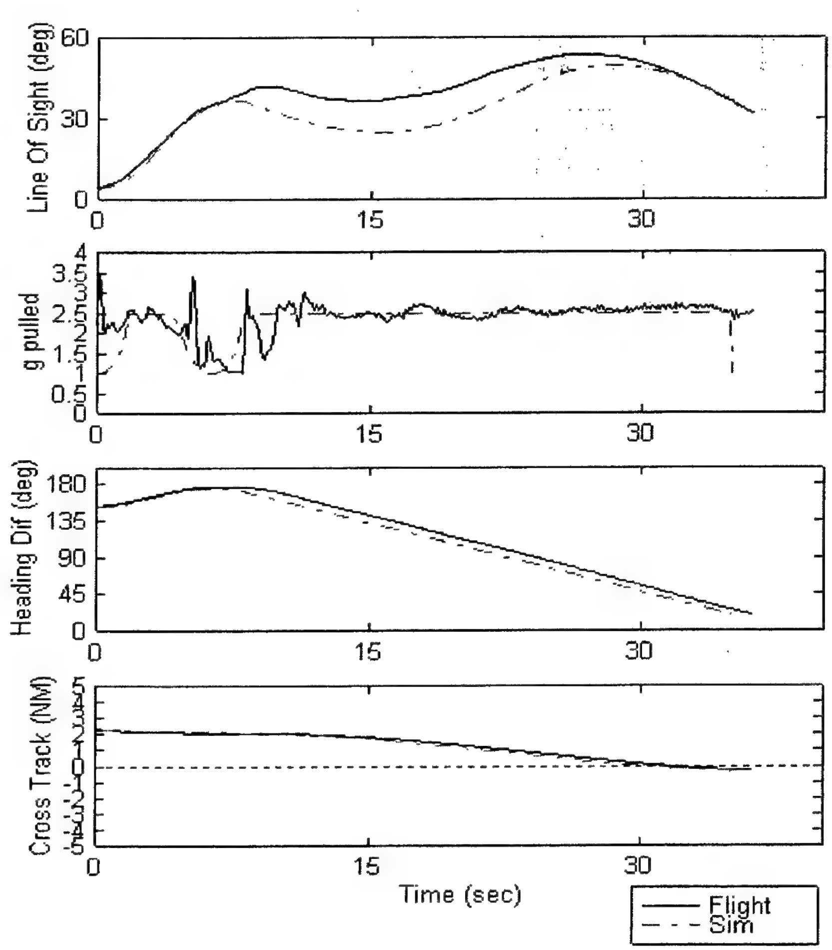
**Planned Intercept Parameters**

Sensor: 40 / 70 (Az° / El°)
Initial Aspect: 150
Range at Open (NM): 4.6
UAV
  Altitude (ft MSL): 20000
  Planned Speed (TAS): 445
  *Actual Avg Speed (TAS): 444*
Tanker
  Altitude (ft MSL): 21000
  Planned Speed (TAS): 417
  *Actual Avg Speed (TAS): 411*




**Simulation/Flight Comparison**

| Parameter | Sim | Flight |
|---|---|---|
| Initial Aspect (deg) | 149.5 | 150.6 |
| Horz Range (NM) | 4.6 | 4.6 |
| Success Criteria? | Yes | Yes |
| Max CT (NM) | 2.3 | 2.2 |
| Max LOS (deg) | 49.5 | 53.6 |
| Max Az (deg) | 34.6 | 39.3 |
| Max El (deg) | 49.5 | 53.1 |
| Min Range (NM) | 1.0 | 1.3 |
| End Range (NM) | 1.3 | 1.6 |
| End Aspect (NM) | -15.3 | -11.2 |
| End ΔHead (deg) | 19.6 | 19.7 |
| Time El is < 0 (sec) (Sensor Breaklock) | 5.2 | 5.2 |




**Comments**

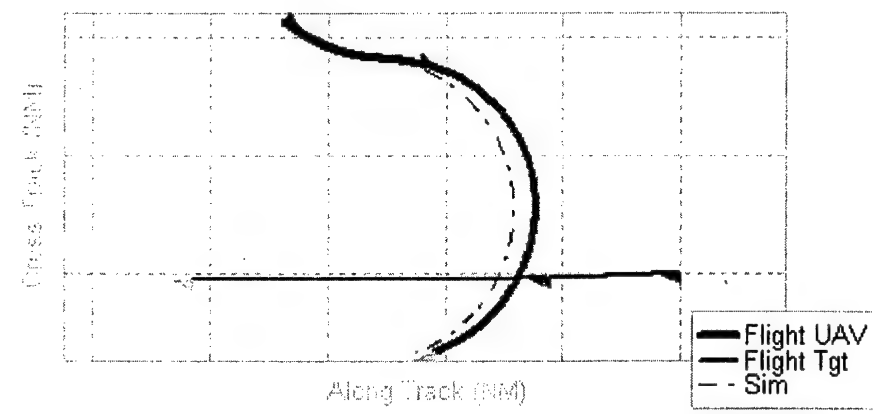
None.

# Intercept 18
## $R_{min}$

Flight 3: 28 Oct 2003

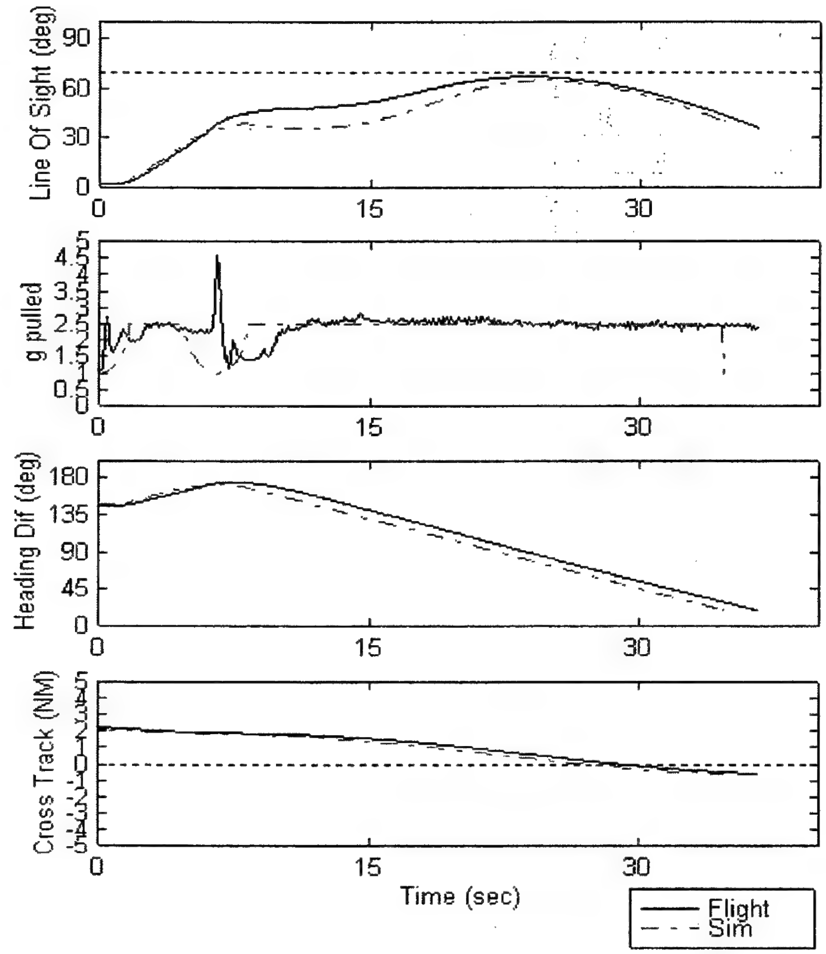
### Planned Intercept Parameters

Sensor: 40 / 70 (Az° / El°)
Initial Aspect: 150
Range at Open (NM): 4.0
UAV
Altitude (ft MSL): 20000
Planned Speed (TAS): 445
*Actual Avg Speed (TAS): 445*
Tanker
Altitude (ft MSL): 21000
Planned Speed (TAS): 417
*Actual Avg Speed (TAS): 410*




### Simulation/Flight Comparison

| Parameter | Sim | Flight |
|---|---|---|
| Initial Aspect (deg) | 147.7 | 145.6 |
| Horz Range (NM) | 4.0 | 4.0 |
| Success Criteria? | Yes | No |
| Max CT (NM) | 2.1 | 2.3 |
| Max LOS (deg) | 64.8 | 67.2 |
| Max Az (deg) | 35.4 | 42.7 |
| Max El (deg) | 61.7 | 65.4 |
| Min Range (NM) | 1.2 | 1.4 |
| End Range (NM) | 1.8 | 2.1 |
| End Aspect (NM) | -19.9 | -16.1 |
| End ΔHead (deg) | 19.8 | 19.6 |
| Time El is < 0 (sec) (Sensor Breaklock) | 5.1 | 6.0 |




### Comments

Initial open of 42° exceeded azimuth limit of 40° which caused an unsuccessful intercept. After the pilot fixed the deviation everything remained within tolerances for the remainder of the maneuver.

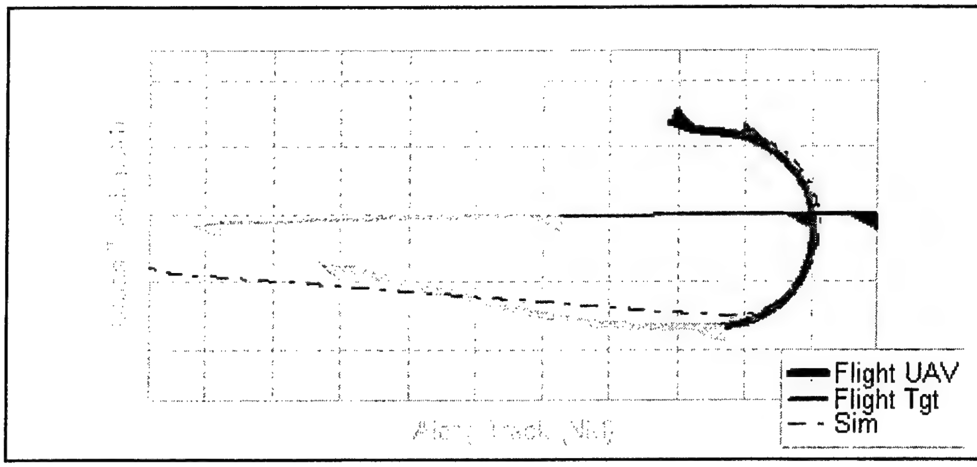
# Intercept 19

## $R_{min\text{-}15\%}$

Flight 1: 8 Oct 2003

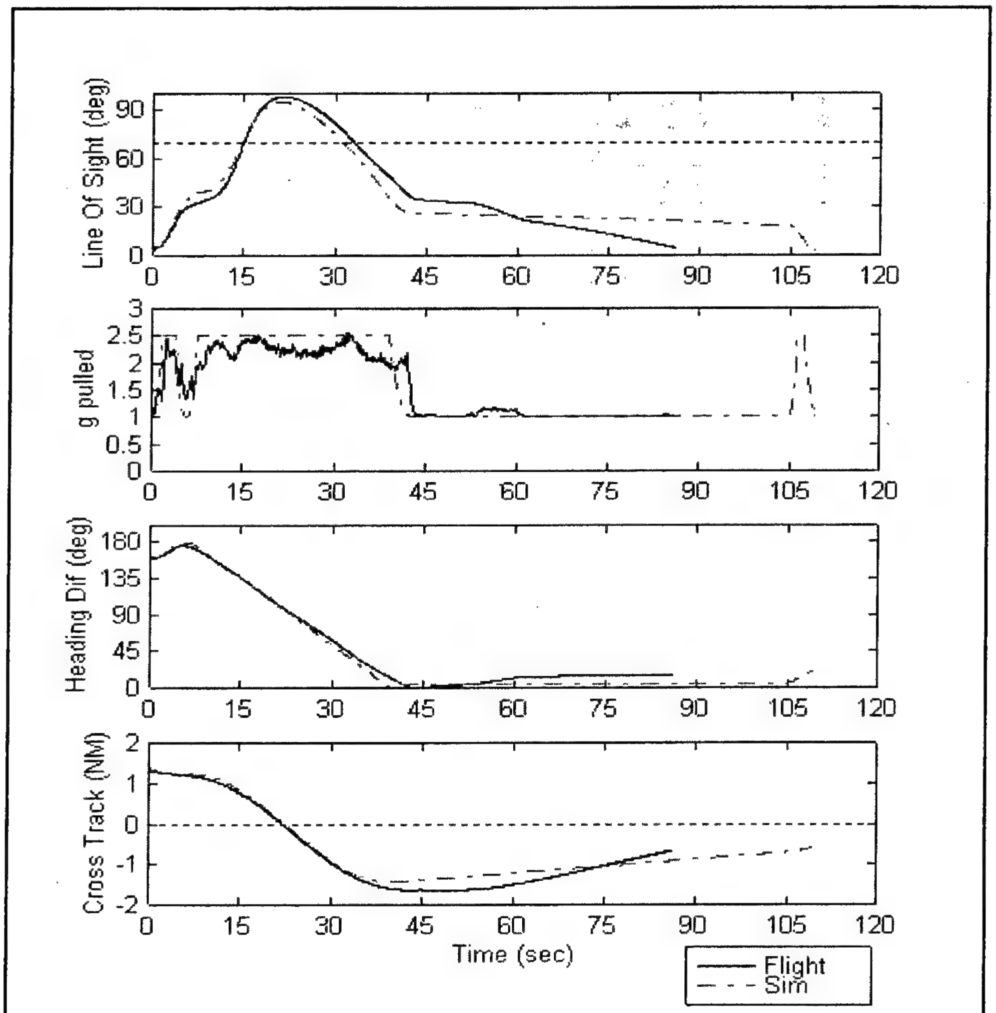
**Planned Intercept Parameters**

Sensor: 40 / 70 (Az° / El°)
Initial Aspect: 150
Range at Open (NM): 3.4
UAV
  Altitude (ft MSL): 27000
  Planned Speed (TAS): 445
  *Actual Avg Speed (TAS): 458*
Tanker
  Altitude (ft MSL): 28000
  Planned Speed (TAS): 417
  *Actual Avg Speed (TAS): 417*




**Simulation/Flight Comparison**

| Parameter | Sim | Flight |
|---|---|---|
| Initial Aspect (deg) | 156.0 | 157.1 |
| Horz Range (NM) | 3.4 | 3.4 |
| Success Criteria? | No | No |
| Max CT (NM) | 1.4 | 1.3 |
| Max LOS (deg) | 95.0 | 98.1 |
| Max Az (deg) | 34.9 | 44.4 |
| Max El (deg) | 88.6 | 91.1 |
| Min Range (NM) | 0.9 | 0.8 |
| End Range (NM) | 1.7 | 2.0 |
| End Aspect (NM) | -20.0 | -20.0 |
| End ΔHead (deg) | 19.6 | 15.5 |
| Time El is < 0 (sec) (Sensor Breaklock) | 5.1 | 4.1 |



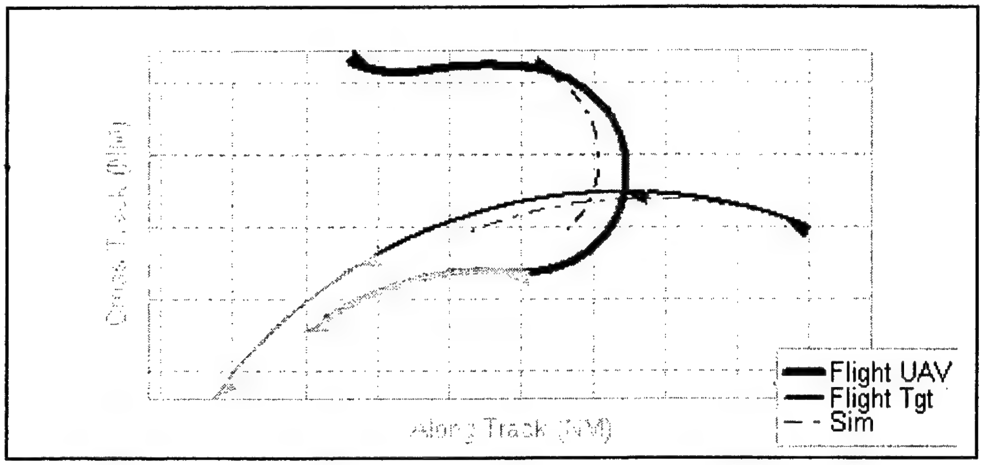

**Comments**

Results closely matched predicted. Pilot closed to pure pursuit instead of cutting to intercept point (more operational but less efficient based on procedures).

# Intercept 21

## $R_{min+15\%}$

Flight 1: 8 Oct 2003

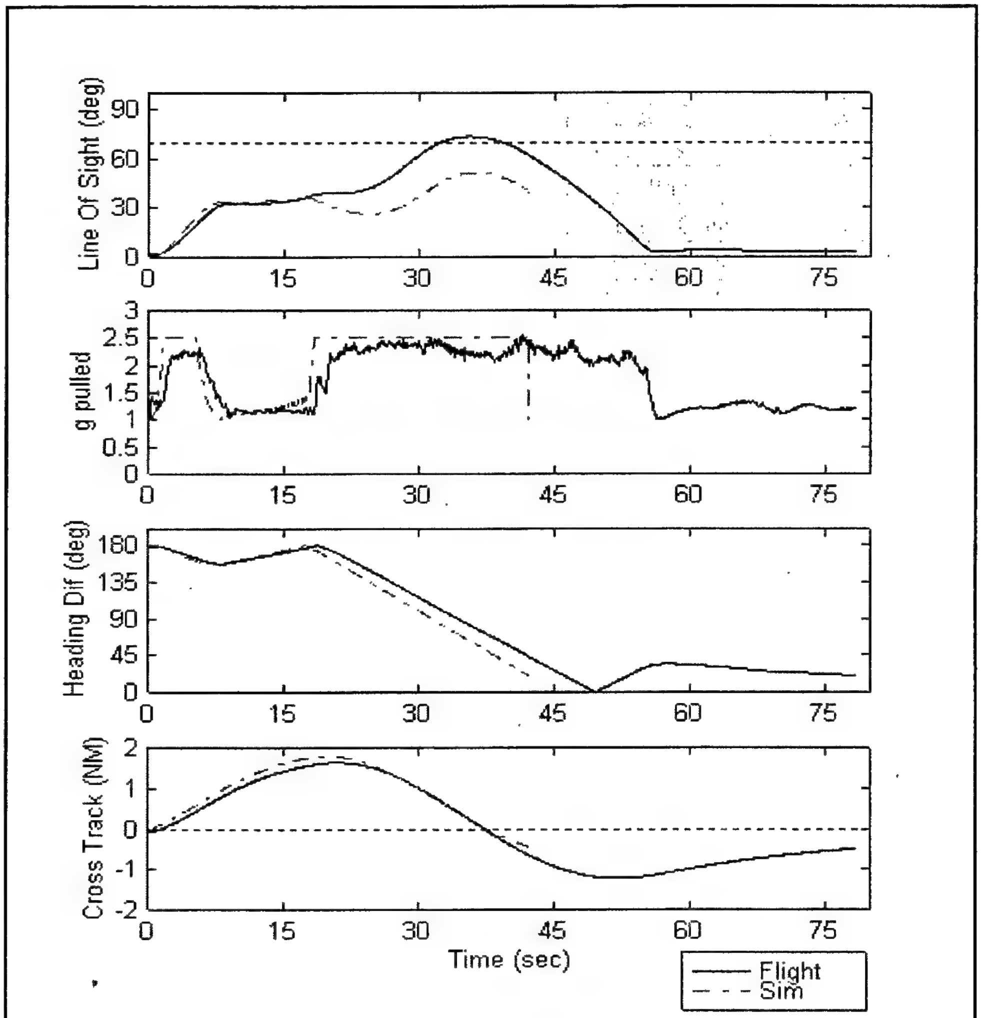



### Planned Intercept Parameters

Sensor: 40 / 70 (Az° / El°)
Initial Aspect: 180
Range at Open (NM): 6.8
UAV
Altitude (ft MSL): 27000
Planned Speed (TAS): 445
*Actual Avg Speed (TAS): 450*
Tanker
Altitude (ft MSL): 28000
Planned Speed (TAS): 417
*Actual Avg Speed (TAS): 416*

### Simulation/Flight Comparison

| Parameter | Sim | Flight |
|---|---|---|
| Initial Aspect (deg) | -179.5 | -179.5 |
| Horz Range (NM) | 6.8 | 6.8 |
| Success Criteria? | Yes | No |
| Max CT (NM) | 1.8 | 1.6 |
| Max LOS (deg) | 51.6 | 73.4 |
| Max Az (deg) | 33.4 | 32.9 |
| Max El (deg) | 49.7 | 66.1 |
| Min Range (NM) | 1.1 | 1.1 |
| End Range (NM) | 1.3 | 1.6 |
| End Aspect (NM) | -19.3 | -18.4 |
| End ΔHead (deg) | 20.0 | 20.0 |
| Time El is < 0 (sec) (Sensor Breaklock) | 6.7 | 6.8 |




### Comments

Maneuver tolerances by both UAVand tanker caused flight to be unsuccessful where the simulation was successful. Lower g and higher airspeed caused excessive turn radius and large line-of-sight. Results showed that tanker parameters were just as important to success as test parameters.

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# APPENDIX G: FLIGHT TEST RESULTS SUMMARY

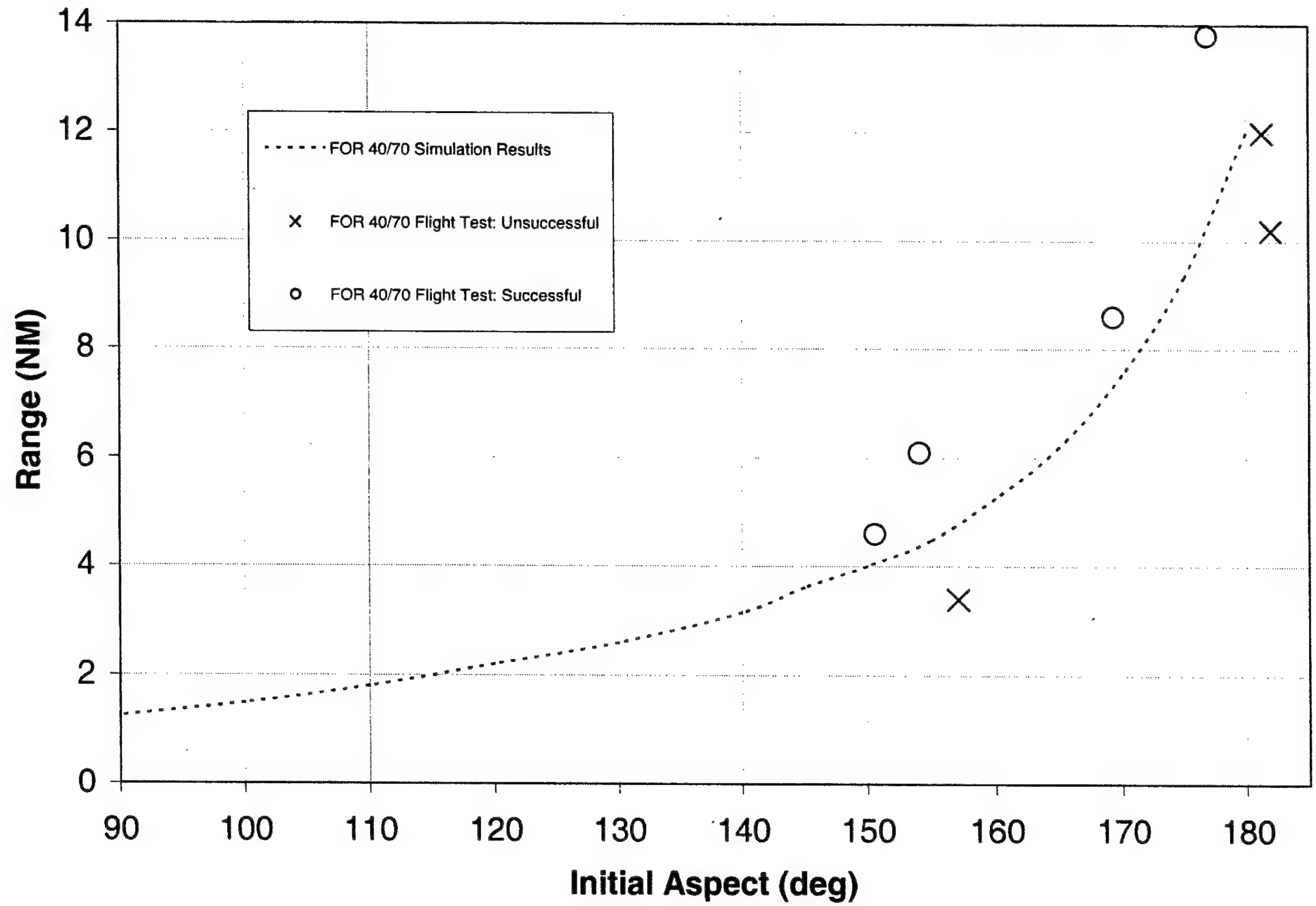


Figure 18. Flight Test Results, 40° by 70° Sensor

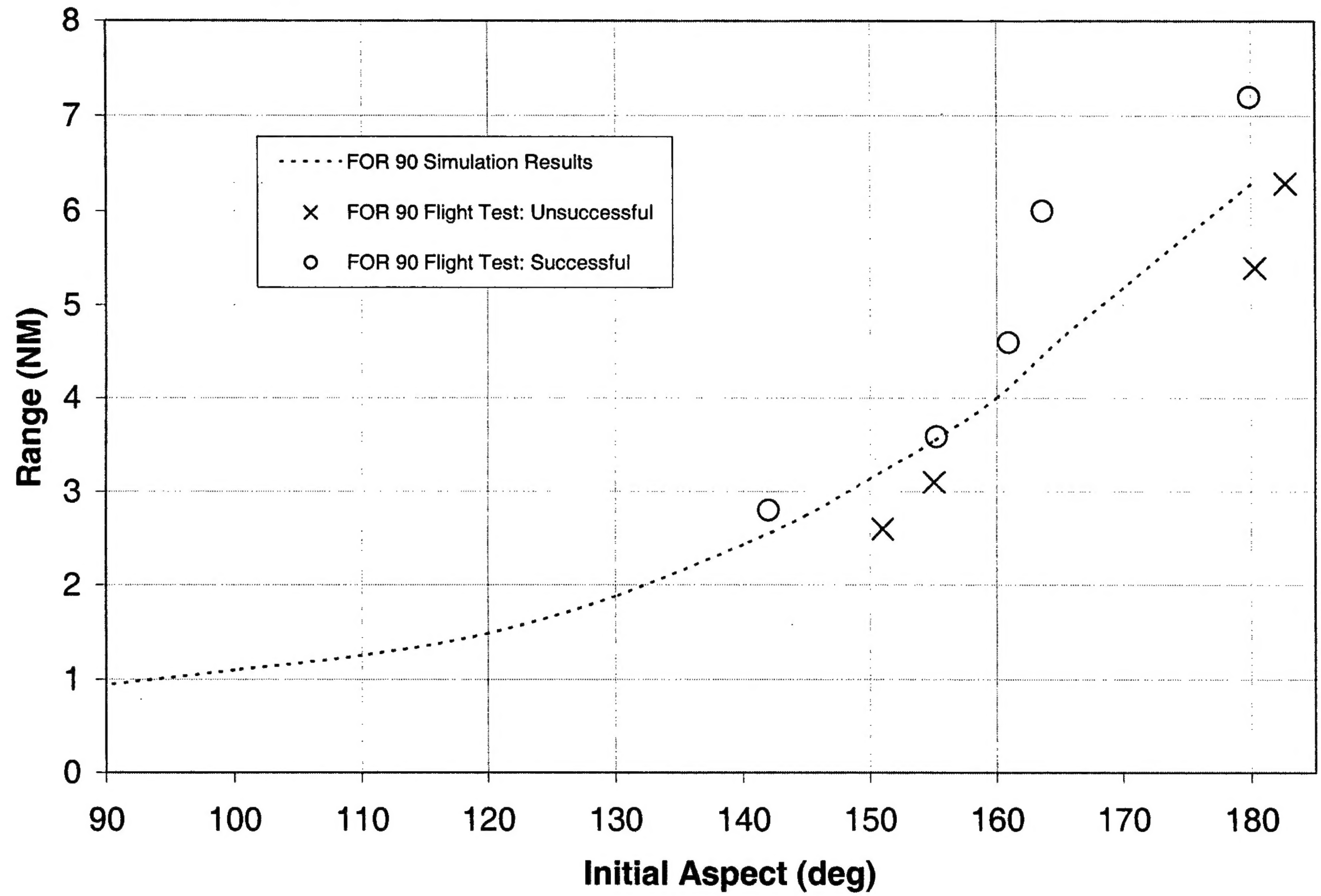


Figure 19. Flight Test Results, 90° Sensor

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# APPENDIX H: DISTRIBUTION LIST

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| USAF TPS/EDC<br>Attn: Ms Dottie Meyer<br>220 S Wolfe Ave, Bldg 1220<br>Edwards AFB CA 93524-6485 | 2 |
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